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TITLE: CORROSION MAINTENANCE AND EXPERIMENTAL DESIGN

By: Robert Summitt
Michigan State University

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This technical report has been reviewed and is approved for publication.

Gary E. Stevenson

GARY E. STEVENSON
Corrosion Control/Non-Destructive Evaluation Group
Systems Support Division

THOMAS D. COOPER, Chief
Materials Integrity Branch
Systems Support Division
Materials Laboratory

FOR THE COMMANDER

WARREN P. JOHNSON, Chief
Systems Support Division
Materials Laboratory

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The objective of this program was to provide external assessments, analyses, experimental design, liaison, and direction in support of logistics-oriented technology research and development programs sponsored by AFWAL Materials Laboratory and the Air Force Logistics Command. The purpose was to provide Air Force program management maximum visibility of the overall direction of efforts in (1) evaluation of corrosion inhibitor effectiveness for aircraft rinsing, (2) improvements to AFLC's Maintenance Data Collection System (MDCS), (3) improvements to base level corrosion severity indices, and (4) adapting corrosion prediction to an airworthiness model.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction

Relative to corrosion research and development, the AFWAL Materials Laboratory consistently has been challenged to identify aerospace corrosion problems which can be addressed and solved by an R & D approach. A corollary to this challenge is to identify the mechanism by which developed technology can be transferred to and implemented by the Logistics and Operating Commands. In addition to existing technologies, those related to corrosion inhibitors, environment characterization, and predictive methodologies have emerged. In view of AFWAL/ML's modest resources in corrosion R & D, it is logical to emphasize programs with high potential for both near-term as well as long-range benefit to USAF operational systems. The transfer of existing technology to operational application should have the highest payoff in cost saving relative to corrosion maintenance.

In the late 1970's and early 1980's, AFWAL/ML conducted four corrosion research studies. One was a combined in-house/contractual effort (Systems Research Laboratories) which led to the development of a water soluble, multifunctional inhibitor system. Although originally proposed for use in the USAF aircraft wash program, no engineering data exist to prove the efficacy of this concept. Michigan State University conducted the other three programs. Two studies dealt with relations between environment and corrosion damage in the C-141A and B-52 fleets. They were based on AFR 66-1 Maintenance Data Collection System (MDCS) and operational-level study of aircraft condition and data reporting practices. A number of system deficiencies were found, and constructively critical comments were reported in various reports (References 1 through 3). These studies established a basis for integrating corrosion prediction with overall aircraft maintenance policies. The third study involved analysis and improvement of the PACER LIME environmental corrosivity index system, originally initiated by Warner-Robins Air Logistics Center (References 4, 5). Subsequently, this base-level corrosion severity index has impacted USAF corrosion maintenance practices around the world and has been used to prioritize capital facilities requests for the USAF-wide corrosion control program.

Because these programs have had obvious economic and operational-readiness implications for all USAF aircraft system, the work described in this report was funded as a two-year effort to explore the following:

(1) The value of aircraft washing/rinsing and corrosion inhibitor additives in corrosion control programs.
(2) Assessment of the improvements to MDCS with respect to corrosion, which were prompted in part by earlier research.
(3) Review and modification of the PACER LIME environmental corrosivity index system.
(4) Advisory assistance in implementing a contractual program to apply previously-developed corrosion predictive capability into Reliability-Centered Maintenance procedures for one or more USAF aircraft systems.

Each of these tasks is discussed in the following sections.

2. Aircraft Washing, Rinsing, and Corrosion Inhibitors

The washing and/or clear-water rinsing of aircraft is considered an essential element of corrosion prevention and control throughout the maintenance structure of USAF (References 6 through 8). Washing/rinsing frequently are mentioned as key elements for improving operational-level maintenance in IG and corrosion survey reports (Reference 9). Such reports, with PACER LIME environmental severity ratings, commonly are cited as supportive evidence for capital facility construction requests.

Theoretical and experimental evidence have shown that certain chemicals inhibit corrosion and corrosion-accelerated fatigue cracking, in much the same way that other chemicals accelerate these processes. Such inhibitor chemicals can be applied to an airplane with good corrosion-prevention potential during routine washing and/or rinsing. A plain-water rinse is thought to be useful for removing corrosive salt deposits, as well as biological, chemical, or radiological contaminants. Inhibitors added to such a rinse would be effective by infiltration into crevices, e.g.,

fastener/metal interfaces or bilges, as well as in the form of aerosols into the airplane interior. Decontaminant agents could be effective in the same fashion, hence the technology related to rinse additives has wide applicability.

The efficacy of inhibitor additives never has been demonstrated, however, nor have the engineering details of process control been developed. A pilot program to add inhibitors to rinse water in order to determine its value was initiated at MacDill AFB (References 10, 11), where an automatic rinse facility exists, but no useful results were obtained. The effort did not succeed for a variety of reasons, but primarily because inadequate consideration was given to logistic and personnel questions in designing the test.

Consequently, today it still is no more than folklore wisdom that rinsing/washing of aircraft (or automobiles) is a cost-effective measure in corrosion control; the benefits never have been demonstrated in any scientific, or even pseudo-scientific experiment. Washing/rinsing probably can remove harmful deposits from exterior surfaces of aircraft. In the absence of convincing evidence supporting the efficacy of such practices, however, it clearly is an inefficient use of increasingly limited public resources for construction and use of facilities for washing/rinsing.

An experimental program, designed by MSU under this contract, can evaluate the efficacy of adding corrosion inhibitors to the fresh water used to rinse salt accumulations from aircraft, as well as the value of aircraft rinsing itself. This program was submitted to AFWAL/MLS as part of Interim Report dated 28 February 1985; it is included here, with some editorial change, as Appendix A. Implementation of this program required funding from AFLC: funding was not planned for FY 1986, but was initiated at the start of FY 1987 by Systems International under contract to Warner-Robins ALC.

3. Assessing Improvements to the Maintenance Data Collection System (MDCS).

In previous research programs, a variety of serious defects in MDCS had been found which severely limited the usefulness of the system for the purposes of corrosion management. These defects were brought to the

attention of AFLC management from time to time; other users of the system also had noted the problems. Indeed, review and criticism of MDCS became quite fashionable. Even the Controller General published in 1983 results of a three-year study (Reference 12) performed at the request of House of Representatives Committee on Government Operations, which reached essentially the same conclusions noted in MSU reports (References 1 through 3). As a result, AFLC changed the system extensively in 1983-84 in order to correct the faults and improve the utility of the data for numerous purposes in addition to its originally designed objective, viz., field-level resources accounting.

An evaluation of the modified MDCS was tasked under this contract to assess the improvements in corrosion tracking and predictive capabilities. A short-term effort was scheduled near the end of FY 1984. It was concluded from this study that the most serious problems of MDCS had been eliminated, consequently a number of meaningful corrosion-related programs can proceed. In particular, "Corrosion Prediction in Airworthiness Models (CPAM)" was initiated with AFLC and AFWAL funding.

One significant change to MDCS was creation of the Maintenance and Operational Data Access System (MODAS), which provides on-line access to the most-recent two years of maintenance and operational data for most USAF systems. MODAS is accessible via several modes, including commercial telephone lines. A computer system has been installed at MSU for access to MODAS in order to continue the evaluation of the improvements, to monitor the aircraft rinse/wash programs, and to monitor the CPAM program.

4. Aircraft Corrosion: Environmental Corrosivity

4.1 Background

Metallic corrosion in the atmosphere is an electrochemical process which requires a film of water (not necessarily visible) on the metal surface. The appearance and disappearance of moisture will vary with a variety of climatic conditions (rain, humidity, wind, temperature, etc.) as well as the presence of contaminants (atmospheric pollutants, oils, etc.) These factors were reviewed thoroughly in an earlier report (Reference 4),

and have been the subject of much research and interpretation since its publication (Reference 13).

Many environmental factors, specifically those related to human carelessness (e.g., beverage spills, poor housekeeping, latrine wastes) are not amenable to predictive modelling; local operating commanders are responsible for instilling habits and procedures which can control corrosion caused by such factors. Most general corrosive environmental factors, however, can be used statistically in corrosion prediction precisely because they are beyond the control of local personnel. These factors include meterological and atmospheric pollutant factors, most of which are measured routinely throughout CONUS and at many other locations worldwide. The more-or-less ready availability of such information, together with the presumed knowledge of the corrodibility of aerospace materials, logically lead to the conclusion that corrosion damage can be predicted, hence corrosion can be managed so as to minimize overall operational costs. This reasoning has spawned a variety of programs aimed at clasifying environmental corrosivity; of particular interest here is the USAF/MSU PACER LIME program.

4.2. The PACER LIME Algorithms

The PACER LIME (PL) system for classifying environmental corrosivity (Reference 4) was developed in response to Strategic Air Command's (SAC) desire to optimize corrosion maintenance costs (e.g., personnel, downtime) for airplanes deployed in diverse environments. AF Logistics Command (AFLC) began the program in 1965 with two objectives:

(1) To develop an algorithm which computes *a priori* environmental ratings from weather and other ambient factors.
(2) To "calibrate" such ratings *via* field testing of selected aircraft alloys.

Interim severity classifications were calculated from a "first-cut" corrosion factor equation and were distributed within USAF in 1972, 1973,

and 1974 (Reference 4). Simultaneously, a field-test program was effected to provide experimental data for comparison with the interim classifications (Reference 5).

In 1978, the program was transferred under contract to Michigan State University (MSU). MSU analyzed experimental results of the field test, the interim "Base Corrosion Severity Classification System," and developed an improved classification system. This system has two central features:

1. Threshold values for known environmental corrodents, established from statistical analysis of observed environmental factors.
2. Algorithms which compare the air-base environment with these threshold values, beginning with the most corrosive to the least, thus resulting in a severity classification for that air base.

Classifications computed from this system for all CONUS air bases and several well-documented field-test sites were compared with published experimental results and with USAF corrosion maintenance experience documented in the Maintenance Data Collection System. The correlation between predicted severity and actual damage was sufficiently good that the classification system was adopted by AFLC, and currently is used, e.g., to determine airplane wash intervals and to prioritize facility capital-expense requests.

Under the current AFSC contract, MSU addressed three PACER LIME related questions:

(1) Are the fundamental assumptions concerning environmental factors and their intensity reflected in more-recent maintenance and field test data? Essentially, this is an updated comparison of algorithm ratings with newer data, particularly those related to pollutants.

(2) Is the air base environment significantly different from that reflected in EPA-type pollutant data measured at the nearest

reporting site? Comparison of more comprehensive data in selected areas with data collected on an air base may provide answers.

(3) The environmental characterization model, PACER LIME, (Reference 4) had not been applied to non-CONUS air bases, mainly because environmental data were not as readily available as for CONUS air bases. A prolonged data collection effort, however, provided the basis for computing corrosivity indices for the non-CONUS air bases. These indices were included in the Interim Report (Appendix B).

The PACER LIME algorithms are based necessarily on a large volume of corrosion data from the literature. The lack of comprehensive world-wide data prompted an effort to collect and compile such data from available sources. Through the efforts of the Principal Investigator, Unit Committee T-3R "Atmospheric Corrosion" of the National Association of Corrosion Engineers tentatively has formed a Task Group to expedite this effort. The accuracy and value of the PACER LIME algorithms depend on the quality of such data. There is reason to believe that the algorithms require modifications so that they will reflect environmental corrosivity more accurately. Concurrent with the data collection effort, the basis for the algorithms is being reevaluated; this effort is not complete. Data accumulation and analysis are in progress. Specific data include the results of atmospheric testing programs published since 1979, and the more detailed environmental data currently available. The data will be computerized to a common format, then correlated by geographical location and date in order to improve the severity-damage correlations used in the P-L algorithms.

The algorithms are based on assumed relative corrosivities of environmental factors, the averaging effect of long-term exposure to them, the utility of mean observed values, and the availability of such observations made locally or at nearby monitoring stations. Several of the assumptions and others related to the purpose of the algorithms, deserve careful re-examination. Moreover, the International Standards organization

(ISO, Committee TC 156) is developing a proposed standard for environmental corrosivity (Reference) which is remarkably similar to the P-L algorithms. In light of these developments, it seems essential that the P-L algorithms should be reviewed carefully.

The original purpose of PACER LIME was to develop a simple method for classifying environmental corrosivity. This classification method was to be based upon readily obtainable data, e.g., weather and atmospheric contaminants. Weather data are available for aerodromes worldwide (Reference 16), but atmospheric contaminant data are available in uniform format only for the United States (Reference 17). Atmospheric contaminant data, however, are collected vigorously throughout most of the world. Consequently, it is quite difficult, though not impossible, to apply classification algorithms to non-CONUS locations. Moreover, there are gaps and deficiencies in EPA data which cause some problems in classifying environments. The problem with EPA data is that the monitoring stations frequently are located in order to control major pollution sources. Very few stations exist to measure "background" levels of atmospheric corrodents. Also, from the corrosion viewpoint, certain kinds of needed data are not reported, e.g., chemistry of particulates.

A simple classification scheme was desired because it was intended to be used for routine logistics decisions concerning fleets of complex system (i.e., aircraft). Many of these decisions can and should be made at the operational level, based upon locally available information. More complex environmental rating systems have been developed since PACER LIME, and still are under development. The more finely-tuned such systems become, however, the less they are a general-purpose tool, hence less useable at the operational level.

A large volume of environmental data has been accumulated since publication of the PACER LIME algorithms. There also is an approximately equal volume of data concerning the effect of environmental factors on metallic corrosion. (A comprehensive bibliography on environmental damage to materials has been published (Reference 18). It should be noted that despite the surfeit of experimental data, critical reviews are nonexistent.) This mass of data, to the extent that it has been reviewed, supports no

major change to the logic or philosophy of the original PACER LIME algorithms. Some minor changes are indicated, however, concerning certain pollutants. First, the effects of ozone, oxides of nitrogen, and particulates are difficult to evaluate, and, moreover, their concentrations are not measured as widely as might be desired. Second, acid precipitation has captured not only the popular imagination, but also has been the subject of serious widespread study. In both areas, there may be good reason to modify the PACER LIME algorithms. Finally, certain problems alluded to above suggest that USAF should monitor air-base atmospheric contaminants. Demands and pressures on existing state and federal monitoring agencies are so great that there is little likelihood any of them can be persuaded to conduct these studies for USAF, especially over the continental/global environments of concern. The costs of such a program (ca. $250,000, including equipment and deployment) are of little consequence, compared with the high value of benefits to be realized.

4.3. Other Environmental Models

There has been considerable world-wide activity to develop models for evaluating environmental corrosivity. Such models are desired for predicting damage to specific materials or systems, and for general damage predictions ranging from statistically-based concepts to finely-detailed explicit formulae. Activities related to model development include (a) environmental correlation and regression-type analysis of corrosion data, (b) an ever-widening network of atmospheric contaminant measuring stations, and (c) the use of environmental chambers in efforts to develop realistic accelerated testing methods and to duplicate real-world corrosion damage in the laboratory. These efforts are supplemented by a stream of environmental corrosion test data and world-wide meteorological data in the form of long-term statistics as well as daily/hourly measurements. Circumstances could not offer much better opportunity for model development. The following is a brief review of selected recent work, especially from eastern Europe. Unfortunately, sometimes it is difficult to decide which of the above categories best describes a specific study.

Mikhailovskii and Skurikhin (Reference 19) have computer processed meteorological data to determine the effect of ambient temperature and moisture on atmospheric corrosion of metals. Corrosion of plain carbon steels, zinc, cadmium, and other metals could be predicted under varying operational and storage conditions from algorithms based on 30 meteorological measurements per month. Mikhailovskii, Strekalov, and Agafonov (Reference 20) also have constructed computer-based physico-chemical models for predicting atmospheric and environmental corrosion of the same alloys, taking account of time of exposure, atmospheric temperature and humidity, and the concentrations of sulfur dioxide and chloride ion.

Egutidze, Dzhinchardze, Strekalov, and Mikhailovskii (Reference 21) determined parameters for predictive calculations of atmospheric corrosion at near marine shore-line sites in a humid subtropical climate. This was based upon a relation between the kinetics of atmospheric corrosion and the electrochemical characteristics of metals in an inactive solution (e.g., borate buffer). Khuntsariya, Sarafov, and Grigorov (Reference 22) performed atmospheric tests of chromated zinc and cadmium coatings at two Black Sea sites. Environmental data are provided for both, as well as test results.

Panchenko, Shuvakhina, and Mikhailovskii (Reference 23) developed an approximate mathematical correlation of aerosol chlorides deposition with shoreward wind velocity and direction. They list experimental chloride deposition data vs. distance from shoreline for six far eastern USSR locations as well as wind data. Additional correlation of experimental corrosion data of steel with theoretical deposition values was presented.

Mikhailovskii and Sokolov (Reference 24) have compared the results of artificial chamber studies with field atmospheric-exposure tests on iron zinc, cadmium, and copper to develop predictive capability with respect to sulfur dioxide. Environmental data are listed for six COMECON tests sites, with reference for test site information. They found that uv radiation was a factor in iron corrosion.

Strekalov, Wo, Mikhailovskii (Reference 25, 26) have performed atmospheric exposure testing of two steel alloys and zinc at eight locations in Viet Nam. They provide detailed geographical location, climatic, and atmospheric contaminant data in numerical form, and corrosion data in

graphical form. Their results can be expressed in the form $K = At^B$, where K is the weight gain in g/cm^2, A and B are constants: B is 0.45-0.55 for Zn, and 0.60-0.86 for steel. Values are tabulated for only three locations; the rest could be estimated from graphical data. Additional data are reported on the chloride and sulfate content of surface corrosion films. Panchencki, Shuvakhina, and Mikhailovskii (Reference 27) evaluated atmospheric corrosion of steel, copper, zinc, cadmium, aluminum, and an aircraft aluminum alloy at inland and marine test sites. Time-of-wetness was calculated from meteorological parameters at the exposure site. Corrosion rates were approximated by a linear function for temperature and chloride concentration, accounting for dilution by rain water. They attempted to account for all factors, including chloride and sulfur dioxide, via regression-analysis-derived equations. Mikhailovskii, Panchenko, and Sokolov (Reference 28) derived mathematical models for predicting corrosion rates of various metals in industrial and marine environments. Environments were classified according to time-of-wetness and the nature of environmental contaminants. Cato and Holtslag (Reference 29) investigated the dependence of air pollution frequency distributions on wind direction for SO_2 in industrial areas of the Netherlands. Metsik and Kalik (Reference 30) studied the effect of climatic factors and atmospheric contamination on the corrosion of steel for different industrial regions of the Estonian SSR. Chemical composition of airborne particulates, especially the presence of ca 4% potassium chloride in the vicinity of power plants employing shale fuel, was a controlling factor on the corrosion rate.

Johansson (Reference 31) studied the effects of SO_2 and NO_2 at constant relative humidity 50 and 90% and 22°C in artificial chambers on the corrosion of steel. A strong synergistic effect was found at 50% RH, but not at 90% RH. Separately, the gases produced only slow corrosion at 50% RH. Carballeira, Drubay, and Carballeira (Reference 32) studied variations of artificial chamber design on corrosion of copper in SO_2 and H_2S in nitrogen. Carvo and Marbot (Reference 33) give SO_2 concentration data for

several locations in Cuba determined by several methods. Wind direction and speed also are used to improve correlations.

The importance of local pollutant sources cannot be overemphasized. For example, Harrison and McCartney (Reference 34) report detailed measurements of nitric oxide, nitrogen dioxide, ammonia, and ammonium nitrate in the vicinity of nitric acid and ammonium nitrate fertilizer plants. Their results show high concentrations of these very corrosive substances at distances up to 4 km from the relevant chemical plants. [It should be noted that the Tampa Bay area (MacDill AFB) contains similar facilities, and coupled with the marine environment, have proved to be highly corrosive (Reference 35, 36). It is not possible to determine at headquarters level whether such local pollutant sources are present at a given air base. The air base DCM must assume responsibility for locating such corrosion hazards, and adjust corrosion maintenance practices accordingly.]

4.4 Environmental Factors: Concentrations, Distributions, and Effects on Materials

Activity continues at a very high level world-wide in determining data experimentally as well as calculating geographical distributions and correlating pollutants and emission sources. Interest in "acid precipitation" is a subject of special interest. Many studies are concerned with pollutant distributions *per se*, whereas others deal with their effects on materials, particularly corrosion. Coupled with extensive corrosion damage studies from atmospheric exposure tests, the prospect for improved statistical correlation of corrosion with environmental factors appears excellent.

The European Air Chemistry Network (EACN) (Reference 37) was established in 1955 to take monthly samples of several chemical species in air precipitation. Nineteen properties of air and precipitation were determined at each complete station each month although some stations sample only precipitation.

Atmospheric corrosion rates vary with the metal alloy, climate conditions, and the airborne pollutants. The nature of the environmental factors, their values, and interactions with various alloys have been reviewed widely (Reference 13). More recent reviews (Reference 38) change the picture very little. We find there is insufficient evidence of corrosion damage by oxides of nitrogen, ozone, and photochemical oxidants to warrant continued inclusion in the P-L algorithms (with the possible exception of the repaint algorithm). Good, widely measured EPA data are not available for these pollutants. Thus environmental factors of concern for corrosion are those related to water, chloride ion sources, and sulfur dioxide concentrations. Where local sources of industrial or agricultural pollutants are present, these also must be taken into account. Further, algorithms for washing and repaint must consider air borne particulates, radiation and oxidants, respectively.

Haagenrud (Reference 38) suggests by implication, a possible modification to the P-L algorithms, viz., the dose/response (D/R) concept. The P-L algorithms compute environmental corrosivity from several statistical means of environmental factors. It is well known that short-time exposure to a corrodant factor at high intensity is more damaging than long-term exposure at a lower intensity, and the increase is non-linear. This is characteristic of chemical kinetics, cf. the doubling of chemical reaction rates with a temperature increase of 10 K. Consequently, the P-L algorithms should reflect the mean value of an environmental factor, and in addition, the maximum value and its frequency of occurrence. The current P-L algorithms take account of the annual mean (50-th percentile) as well as the statistical maximum (99-th percentile).

A variety of different approaches have been taken by other workers in efforts to characterize environments. These include detailed measurement of local conditions coupled with simultaneous corrosion testing and mathematical regression analysis; more elaborate characterization models based on environmental factors, in a manner similar to P-L, and even adopted as national and international standards; and extensive efforts to reproduce field corrosion damage in the laboratory using environmental test chambers. At the same time, the literature of atmospheric monitoring and corrosion

testing has increased considerably. Indeed, there may be enough such data that there could be a moratorium on testing, except for special case requirements, until the existing data have been digested properly.

At best, these studies demonstrate that actual environmental conditions, hence corrosion rates vary considerably over short and long time periods. Such variations are not predictable, except for long-term mean and extreme values for the several environmental parameters. In addition to the time variability, consideration also must be given to differences between the macroenvironment (i.e., the environmental factors values averaged over a substantial area, say an acre or a square mile) and the microenvironment (i.e., values at a specific corroding site, say the nose or chin of a bronze statue). None of these variations can be modelled with mathematical precision; they can be treated with some measure of success only by a statistical approach such as that of PACER LIME. The predictions of several other approaches have been reviewed. On the surface, they appear to be more sophisticated than P L, but in fact they are not better, and often worse, than those of the simple P L.

The difficulty of defining precisely the microclimate and corrosivity of two exposure test sites close to one another (the 25-m and 250-m test lots at Kure Beach, NC) is well illustrated by Baker and Lee (Reference 40). A variety of environmental factors at these sites were monitored carefully over a thirty-year interval and the results were presented with corrosion rates of several metals exposed at these sites. Their results clearly illustrate the futility of predicting corrosion damage of a specific alloy exposed at a given site from local environmental factors. Only a statistical approach has any realistic chance of success.

Knotkova-Cermakova and Barton (Reference 41) describe the Czekoslovak system of standards for classifying environmental corrosivity. Their methods closely parallel those of PACER LIME, but carry the classification system to finer detail. Czekoslovakian standard, CSN 03 8206^{+}/ST SEV 458-77, "Dividing the earth's surface into climatic regions for technical ,purposes," defines the effects of temperature and humidity into seven classes:

Very cold	EF	Tropic arid	TA
Cold	F	Moderately cold sea	H
Moderate	N	Marine tropic	MT
Tropic humid	TH.		

Then CSN 03 8805+/ST SEV 460-77, "Types of the climatic performance of products," defines four types of exposure, ranging from "boldly exposed in the atmosphere" to "in enclosed spaces with artificial control of climatic conditions" (timidly exposed?).

Finally, the presence of corrosive accelerants, mainly chloride and sulfur dioxide, is accounted for in CSN 03 8203+/ST SEV 991-78, "Classification of the corrosion aggressivity of the atmosphere," which defines five degrees of corrosivity, based on the corrosion rates of engineering metals in atmospheres with various levels of contamination and in different locations. Another standard, CSN 03 8204, "Determination of the corrosion aggresivitiy of atmospheres for metals and metallic coatings," describes empirical methods for determining atmospheric corrosivity.

The main use for these classification methods is in the selection of an economically optimum corrosion protection system for fixed structures or devices. In the case of steel structures for example, five major environmental degrees of corrosivity are defined, each with two or three minor degrees, to produce a total of thirteen environment classes.

Another PACER LIME-similar life-predictive model, based on coupon exposure at numerous locations, has been developed by Battelle Columbus Labs for prediction of electronic equipment service life in a given atmosphere (Reference 42). This model also is simple and attempts to predict the amount of tarnish, oxide, or corrosion on selected materials in computer or electronic control rooms from measurements of oxide thickness and duration of the test. Atmospheres for a specific location are categorized into one of five corrosive categories based on parts per billion (ppb) of contaminants. Although the logic of this program parallels that of P L and the proposed ISO standard (Reference 15), its focus is materials damage at far lower contaminant concentrations in a "controlled" environment.

5. Corrosion Prediction in Airworthiness Models

5.1. Background

Assurance of a safe and functional aircraft can be achieved best on the basis of a comprehensive airworthiness maintenance model (CAMM). This model should combine the following:

(1) Fatigue-life prediction from the Aircraft Structural Integrity Program (ASIP).
(2) Non-destructive evaluation (NDE) programs and results.
(3) The concepts of Reliability-Centered Maintenance (RCM), (References 43,44).
(4) Corrosion prediction methodologies.

Corrosion is both critical and ubiquitous. Although ASIP, NDE, and RCM are highly sophisticated, all of them give only lip-service to the corrosion problem. RCM specificaly dismisses consideration of corrosion, because "Like fatigue, corrosion is age-related. It is not nearly so predictable, however, since metals corrode at rates that depend on a complex of environmental conditions and maintenance practices (Reference 43). This plainly absurd viewpoint argues that RCM is not applicable to corrosion, because corrosion has precisely the same characteristics as fatigue cracking, where RCM has succeeded so spectacularly!

Corrosion maintenance requirements in the past were based either on inspections, which reveal a need for repair, or on a calendar/isochronal basis. Inspection methods are inadequate to prevent undetected damage in inaccessible locations from reaching critical levels. It has been shown (References 2, 3) that predictive models can be based on environmental factors correlated with empirical corrosion failure data. Such a model then can be integrated with RCM into the airworthiness model, with NDE assuming a supportive rather than a primary role.

The program to achieve this goal will involve materials and processing, operations research, structural engineering (including fatigue and fracture mechanics), aircraft maintenance, environmental factors,

modeling methodology expertise, and the characteristics of corrosion and crack-growth kinetics. Accurate maintenance data (MDCS) - can be used to provide coefficients for the appropriate predictive equations, which then can be used to supplant inspection methods. A practical predictive model must be developed from intimate familiarity with the structure, such as that possessed by a prime airframe contractor, and must be based upon stochastic forecasting techniques using aircraft maintenance and operational data.

The predictability of corrosion damage to an aircraft fleet has not been readily accepted. Numerous objections have been raised, and conceptual and procedural problems have been pointed out; RCM texts explicitly reject the proposition. Some of the questions address valid points; we have tried to answer them where possible, but further research is often needed. Some questions are unimportant. Because of this controversy, however, we try to explain carefully the logical basis and the procedural methodology whereby corrosion processes in general, and variable environmental severity specifically, can be used to predict fleet damage from a statistical basis. We do not propose specific models, except for the PACER LIME environmental characterization algorithms, nor do we consider specific systems. These questions currently are being addressed by the Lockheed-Georgia Company under contract to USAF, Dr. R.N. Miller, Program Manager. Models used in this report are for illustrative purposes only.

5.2. Forecasting Models

Much related discussion on this problem has been published elsewhere (Reference 3); some material is reproduced here.

An aircraft structure may be corroded at one or more locations, and failure may occur when the extent of corrosion at one location reaches a critical state. Corrosion initiates at randomly-distributed points of high Gibb's free energy, hence initiation is a random process. Once initiated, the progress of corrosion follows the laws of chemical kinetics. Initiation and propagation both are predictable in terms of well-developed mathematical models. These can be fitted to a specific problem by empirically establishing values for their several parameters using data collected in a

corrosion monitoring program. This empirical data will describe, as a function of time, the onset of corrosion, its extent, the corrodibility of specific metals, and the severity of environmental corrosiveness. Consequently, the extent of corrosion damage y to a specific component, at time t, in a constant environment described by parameters x_i, may be expressed conceptually as

$$y(t, x_i) = P(t, x_i)\, f(t, x_i), \tag{1}$$

where $P(t, x_i)$ = probability function that corrosion will start, and

$f(t, x_i)$ = kinetic function of time and variables; frequently the time dependence= at^N, where a and N are constants related to the environment.

The problem is simply to fit empirical data for a statistically-significant set of components to appropriate models.

An airplane's service history is a discrete set of events defined by environmental conditions (e.g., flying hours by mission type, time spent at various air bases, weather at those air bases.) Corrosion damage, measured, say as manhours required for repairs at time t, may be expressed as a function of the t_i spent for each event or condition x_i, e.g.,

$$y'(t, x_i) = a_o + a_i x_i + a_{ij} x_i x_j + a_{ijk} x_i x_j x_k \tag{2}$$

using the Einstein summation notation. It is understood that a_i and x_i need not be simple factors, each might be a complex function of time and a specific environmental factor. Cross terms represent synergistic interactions between environment factors, e.g., between salt and moisture. The a_i are risk "coefficients" for each factor or combination of factors. Thus maintenance could be scheduled for system or subsystem when $y(t, x_i)$ reaches a predetermined value for some critical component or for the entire airplane, hence maintenance would be based upon a statistically demonstrated need for repair. One requires only the analytical form of Equation 2. Such

relations are available for <u>specific</u> environments, where all factors relating to corrosion are known and constant.

In more complex environments, such as field test sites, empirical equations have been developed for specific alloys. Weight gain data, ΔW for commercial low-alloy steels exposed at an industrial test site in northwest Indiana were found (Reference 45) to fit the equation

$$\Delta W = Kt^N , \tag{3}$$

where K and N are empirical constants. Similar relations should exist between aircraft operational histories ("environment") and corrosion maintenance records, hence cost and repair frequency should be predictable from environmental factors.

A deterministic corrosion-life/cost-prediction model would predict the state of damage under the worst case of environmental exposure. Computed corrosion rates then would calculate when an inspection would detect a specific population of components which have suffered a preselected extent of damage. At that inspection, components are retired for cause (RFC), or inspected and repaired as necessary (IRAN) according to the optimum cost equation. Since corrosion generally is not critical to safety of flight, there will be considerable latitude in selecting population and damage extent, as contrasted with fatigue cracking. Consequently, costs of RFC/IRAN are more significant in optimizing inspection intervals than is the extent of damage <u>per se</u>.

The foregoing logic describes a reasonable approach to damage prediction. A similar logic is being used to construct national damage/cost models to address economic issues in the National Acid Precipitation Assessment Program (Reference 46). We do not believe that USAF requirements for corrosion in CAMM are this detailed. CAMM should be based on a simple environmental severity mode, e.g., PACER LIME, metal corrodibility, and statistically-based corrosion prediction, all integrated into RCM.

5.3. The Statistical Basis of Corrosion Prediction

Statistically-based corrosion prediction is discussed as follows: Five sections, containing premises and discussions, provide the basis for analytical discussion in a sixth section.

5.3.1. Corrosion initiation is a stochastic process described by a probability function, P(t), which depends on the metal and environmental conditions. At one extreme, P(t) is so narrow that the time interval between exposure and the onset of corrosion is short and cannot be measured. An example would be immersion of zinc into aqueous 1 N hydrochloric acid. At the other extreme would be a well-passivated metal which exhibits no detectable corrosion within an experimentally convenient time period. For metal/environment systems of interest, however, the onset of corrosion of individual identical specimens exposed to the same environment will occur over a finite time interval.

Experimental determination of such probability functions has received little attention, in part because most corrosion testing procedures are experimentally unsophisticated. The fault lies with the "nature of the beast," however, and not with those who do the experiments.

5.3.2. The rate of corrosion, following initiation, is determined by environmental factors and may be constant or vary with time. If environmental conditions are constant, the corrosion rate equation will not change. (The corrosion mechanism may change, of course, as corrosion products accumulate on the metal surface, but this is assumed to be known.) Consequently, the extent of corrosion damage can be predicted at any time after corrosion begins.

From the two preceding arguments, the most important contribution to experimental error in corrosion testing is the initiation probability function.

5.3.3. If environmental conditions are changed, then the corrosion rate also changes. Indeed, the process can be interrupted if, for example, the necessary film of moisture evaporates. Abrupt large changes in local

environmental conditions are possible, but rare, hence corroding systems are exposed to reasonably uniform conditions.

5.3.4. The local environment consequently, can be characterized by an appropriate combination of the ambient corrosive factors, including mean values, their annual or monthly ranges, and the most probable maximum values. The only environmental factors which need be considered are meteorological data, together with sulfur dioxide, chloride aerosols/particulates, and perhaps, precipitation acidity. The PACER LIME logic and algorithms offer the most rational approach to environmental characterization for factoring corrosion into maintenance and logistics decisions.

5.3.5. Environmental severity will affect the shape of P(t) as well as the kinetic rate equation. The effect on the probability function may be illustrated with reference to a Gaussian distribution function (although we do not know whether such a function represents corrosion initiation).

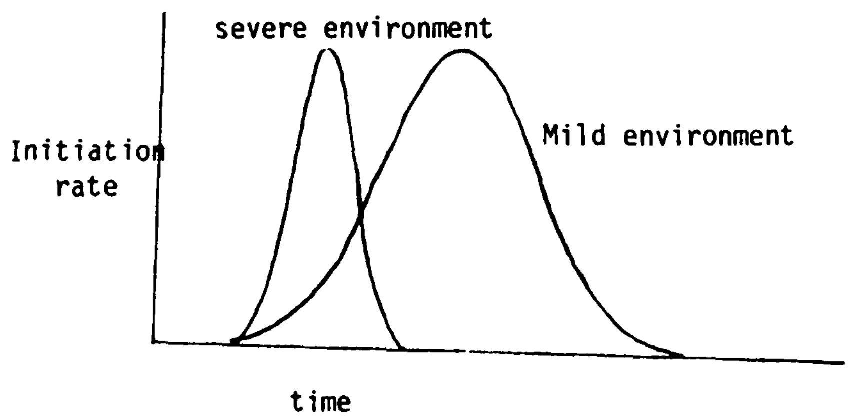

Figure 1. Gaussian Model of Corrosion Initiation Probability in Varying Environmental Conditions.

In a severe environment, the mean time to corrosion initiation is shorter than in a mild environment. Moreover, the rate of initiations, expressed as the time interval in which a given fraction of the population will have started to corrode, is higher for the severe environment. Mathematically, these are expressed by the coefficients A and B, positive constants that determine the width, and the position of the peak, respectively, in the defining equation

$$P(t) = C \exp\left(-\frac{1}{2} At^2 - Bt\right), \quad (-\infty < t < \infty); \tag{4}$$

C is the normalization constant,

$$C = \left(\frac{A}{2\Pi}\right)^{1/2} e^{-B^2 2A}. \tag{5}$$

The environmental effect on the rate equation may be illustrated by a simple exponential function for cumulative damage to one unit or specimen

$$c = k\, e^{-(t-t_o)},$$

where t_o is the onset time and k is a scaling factor which can express environmental severity, Fig. 2.

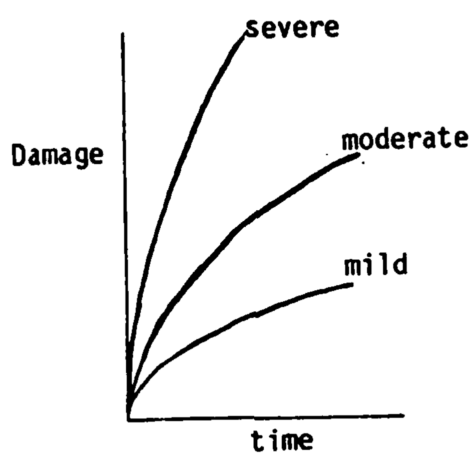

Figure 2. Corrosion Damage in Different Environmental Conditions.

5.3.6. A grand cumulative damage function GDF for a fleet of aircraft may be applied to structural condition or to a specific component on each

individual aircraft: GDF is obtained from integration of the probability and damage functions. This integration is illustrated in a simplified manner by consideration of discrete intervals for both functions.

In Figure 3a, a Gaussian distribution for a set of airplanes is shown as a function of the time of initiation, t_o. This distribution is divided into discrete time intervals of length T in Figure 3b, where each interval contains a discrete set of airplanes n_i, which have begun to corrode in that interval. Clearly, airplanes which begin to corrode at earlier times will exhibit more advanced deterioration than those which start later. These "early birds," however, are fewer in number, hence their contribution to cumulative fleet damage is proportionately less.

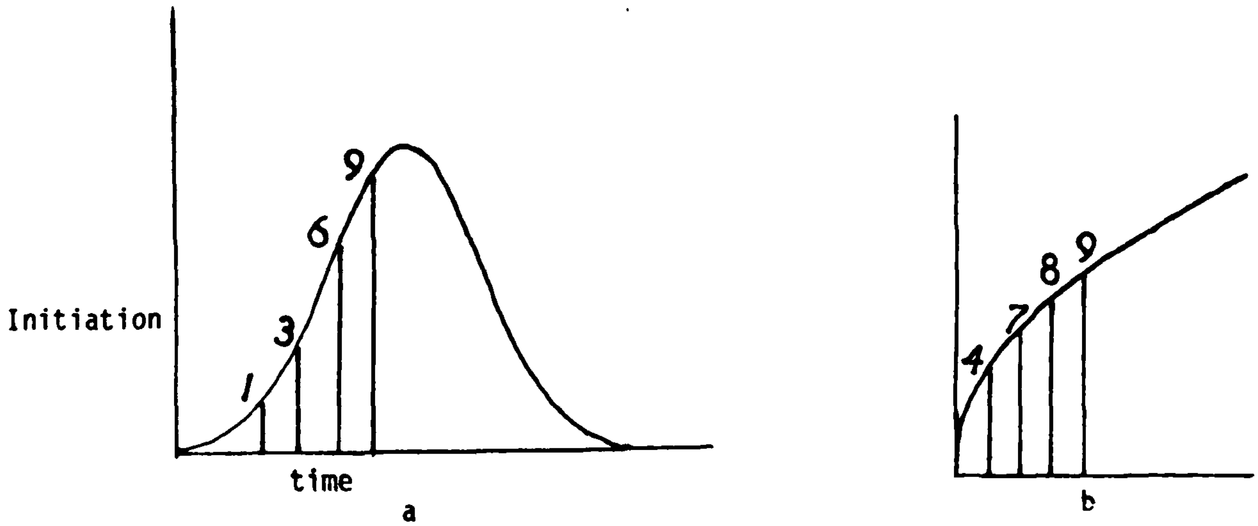

Figure 3. Continuous and Discrete Corrosion Initiation Probabilities.

Next, we follow the extent of damage of each set n_i in time intervals of length T_i subsequent to corrosion initiation. Damage is assumed to be exponential Fig. 2. (In this model, incremental damage decreases with time, thus offsetting somewhat the early start. This is an artifact of the model chosen for illustration, and need not represent an actual situation). In time interval $T_1 + t_o$, n_1 airplanes started

corroding, while $N\text{-}n_1$ remained pristine. The damage to these n_1 airplanes in time interval T is c_1, represented in Fig. 4 at the upper left by n_1 horizontal lines of length c_1, represented by x's. The representation is continued horizontally: The second column entry of lines of c_2 length shows the damage to the first set after 2T; in the third column, n_1 lines each of c_3 length illustrate the damage after 3T, etc.

Meanwhile, in interval T_2, n_2 airplanes have started the process, but their damage at the end of 2T is only c_1 each, since this is their first time "at bat." Thus a second row of entries begins at column 2, consisting of n_2 lines of c_1 x's. The second row entry at 3T is n_2 lines of c_2 x's, etc. There is no line 2 entry in the first column because this subset experienced no corrosion. The table is continued downward to initiation interval T_3, T_4, etc., and each entry consists of n_i lines each of length c_1, c_2,... with c_i corresponding to the initiation interval.

At any particular time, it is possible to predict the number of airplanes in the fleet which have reached a specific damage level. This damage level might be selected for optimum time of repair at minimum cost, or for a critical damage condition, reduced by an appropriate safety factor. There are a variety of other selection criteria. It is not possible to predict damage to a specific airplane, although the method could be applied to components which are numerous, e.g., skin fasteners. It also is not necessary that all units enter service at the same time.

PROPAGATION INTERVAL

	1Ω	2Ω	3Ω	4Ω
1τ	1 x 4	1 x 7	1 x 8	1 x 9
	xxxx	xxxxxxx	xxxxxxxx	xxxxxxxxx
2τ	3 x 0	3 x 4	3 x 7	3 x 8
		xxxx	xxxxxxx	xxxxxxxxx
		xxxx	xxxxxxx	xxxxxxxxx
		xxxx	xxxxxxx	xxxxxxxxx
3τ	6 x 0	6 x 0	6 x 4	6 x 7
			xxxx	xxxxxxx
			xxxx	xxxxxxx
			xxxx	xxxxxxx
			xxxx	xxxxxxx
			xxxx	xxxxxxx
			xxxx	xxxxxxx

Figure 4. Discrete damage conditions assuming Gaussian initiation probability and parabolic kinetics.

The same result can be expressed in integral form. It is noted that two running "time clocks" are relevant to the problem: (a) one for the initiation probability, and (b) a second for the extent of corrosion damage subsequent to initiation. We do not consider the relative "speed" of these two clocks, but consider them approximately comparable. Referring to Figures 5 and 6, it should be remembered that the abscissae, designated t and T, respectively, are related proportionally but in general they are not the same scales. In Figure 5 is plotted a Gaussian distribution, dn/dt vs. t, and in Figure 6, a representative corrosion damage growth curve, D(T).

We define a corrosion damage threshold $\tilde{D}$ as the level at which various maintenance options might be exercised for a specific corroded component/system to achieve optimum cost. Such maintenance options might be inspection and/or on-condition repair. Alternatively, an RFC program might be initiated, although "cause" would not be the result of a specific inspection. It would instead resemble the "hard-time" concept of TCTO's, but here "hard-time" is a statistically determined value.

The corrosion damage threshold $\tilde{D}$ for a single component/system is reached at corrosion "clock" time. If the damage function is expressed as

$$D(T) = kT^{p},$$

then

$$T = [D/k]^{1/p}.$$

Consequently, we are interested in the number of components/systems which have initiated corrosion at time $t = \tilde{T}$. Since these will be damaged to the threshold level, the remaining N-n will not have initiated corrosion at an early enough time to have corroded to the threshold level. Again, note that the time interval T plotted on Figure 5 in general is not equal to the equivalent interval on the abscissa.

Finally, since the number n(t) which have initiated corrosion is given by

$$n(t) = \int_{o}^{t} \frac{dn}{dt}\, dt,$$

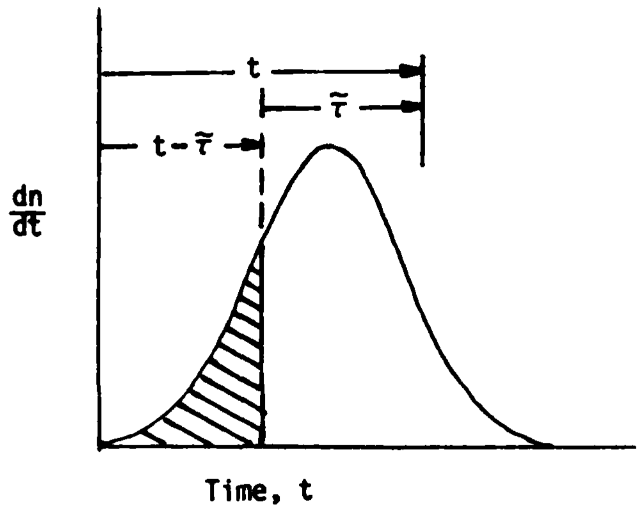

Figure 5. Corrosion to Threshold Damage Level.

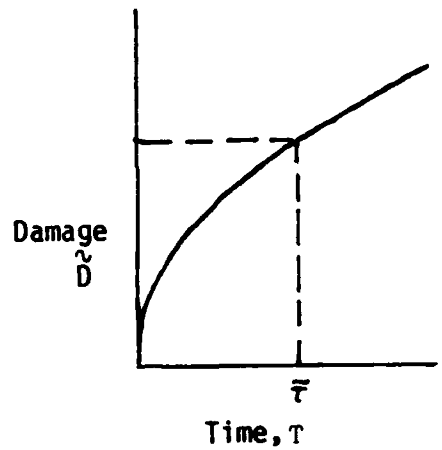

Figure 6. Parabolic Damage to Threshold Level.

it follows that the number of systems n(t) which have passed the threshold damage level at time t is

$$n(t) = \int_o^{t-T} \frac{dn}{dt}\, dt = \int_o^{t-(\tilde{D}/k)^{1/p}} \frac{dn}{dt}\, dt.$$

This is the area under the curve dn/dt vs. t between t = o and t = t - T. Tabulated values of these integrals have been published for the Gaussian distribution function as well as a variety of others (Reference 47). Integration also can be done with computers and numerical methods.

6. Conclusions and Recommendations

6.1. Conclusions

6.1.1. The efficacy of Fresh Water Rinsing in Aircraft Corrosion Control.

An experimental program was designed which would determine the value of corrosion inhibitors added to fresh water used for rinsing aircraft. This program was intended to be applied to F-16 aircraft assigned to MacDill AFB FL, where an automatic taxi-through rinse facility exists. The program has not been implemented, however, because use of the automated rinse facility is not compatible with operational practices at MacDill. Moreover, it is not clear that fresh water rinsing itself is beneficial in a corrosion control program. A new program will evaluate first the efficacy of fresh water rinsing.

6.1.2. Assessing Improvements to the Maintenance Data Collection System (MDCS).

An evaluation of the modified MDCS concluded that its most serious problems had been eliminated. Moreover, the recently-added Maintenance and Operational Data Access System (MODAS) has greatly increased the availability and utility of MDCS data. Consequently, a variety of corrosion-centered programs are made possible, particularly Corrosion Prediction in Airworthiness Models (CPAM).

6.1.3. Environmental Corrosivity.

The PACER LIME (PL) system for classifying environmental corrosivity was applied to USAF non-CONUS air bases using data collected in this program. The PL algorithms should be modified on the basis of recent corrosion and environmental research. Such modification was not completed in this program.

6.1.4. Corrosion Prediction in Airworthiness Models (CPAM).

The mathematical basis for merging corrosion prediction with Reliability-Centered Maintenance has been extended.

6.2 **Recommendations**.

6.2.1. Aircraft Rinsing.

Costly fresh water aircraft rinsing is required for aircraft operated at low altitude over salt water. Automated rinse facilities exist at several locations and are in popular demand. There is no convincing evidence that rinsing is of benefit. If it is beneficial, then clearly corrosion inhibitors added to the rinse water could enhance the benefit. An evaluation program following the outline recommended here should be implemented to determine the answer to this question.

6.2.2. Environmental Corrosivity.

The PACER LIME environmental corrosivity algorithms should be reviewed in light of recent corrosion and environmental research and modified as necessary in order to reflect more accurately the severity of various environments. Since the air base environment is somewhat different from those monitored by the US Environmental Protection Agency, a program should be implemented to determine the nature and corrosivity of atmospheric factors in the air base environments.

6.2.3. Corrosion Prediction in Airworthiness Models (CPAM).

The mathematical basis for merging corrosion prediction with Reliability-Centered Maintenance should be developed on a practical basis for a specific airframe system, and the results extrapolated to other

systems as early as possible in order to reap the benefits of this technology.

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APPENDIX A.

The Efficacy of Fresh Water Rinsing in Corrosion Control of Aircraft

An Evaluation Program submitted to
AFWAL/MLS - Systems Support Division
Wright-Patterson AFB

by

Robert Summitt
Michigan State University

Interim Report
28 February 1985

Revised 28 February 1986
Contract No. F33615-84-C-5066

Abstract

An evaluation program is described which will provide documented evidence concerning whether an automatic fresh water rinse facility at MacDill AFB is of value or is harmful in controlling corrosion in F-16 airplanes. The program is to span one year. It will involve both a fresh water rinse and an inhibited fresh water rinse. Coordination of the program at MacDill will be effected by a local contractor. Management and funding will be provided by AFLC, and evaluation of the results will be performed jointly by AFLC, AFWAL, and MSU. The program will be monitored by MSU using a variety of information sources. There will be no interference with MacDill TAC operations, nor will any participating effort be required of MacDill personnel.

The Airplane Rinse Facility at MacDill AFB: To Rinse or not to Rinse,...

1. Introduction

Aerosols, industrial and agricultural dusts, and engine exhausts accumulate on directly exposed aircraft surfaces as well as within open wheel wells, service bays, and cockpits; most such deposits, particularly salt, are corrosive as well as unsightly. Accordingly, it is USAF practice to wash aircraft, at 30-60-120 day calendar time intervals according to the concentrations of such airborne contaminants, in order to remove corrosive soils as well as for cosmetic enhancement. Whether soils are harmful-or at least more harmful than harsh washing detergents and vigorous scrubbing-is debatable from a technical standpoint. Obviously a clean airplane is less unattractive than a dirty one.

Near the seashore or other salt sources, the environment is especially severe. At MacDill AFB, salt deposits may accumulate as rapidly as 5 g/day on the upper surfaces of a typical interceptor/attack airplane. The U.S. Navy operates aircraft in similarly severe environments and schedules washings at 14-day intervals, compared with the shortest USAF interval of 30 days. Even this 14-day interval is considered excessively long, and fresh water (or foam surfactant) rinsing is required for certain operational conditions, e.g., shipboard or low-altitude flight over salt water. Such rinsing produces no improvement in appearance, particularly on matte-finished aircraft, hence it is only of value in corrosion prevention; USN corrosion experts believe rinsing is effective (References 1, 2).

Aircraft rinsing is costly both in man-hour and fresh-water consumption, but automated, taxi-through rinse facilities significantly reduce these costs; USN operates at least five such facilities on the eastern US seaboard, and they are in considerable demand within USAF (Reference 3). The value of the fresh water rinse in preventive maintenance, like the value of washing, has never been demonstrated, but rests instead on "folklore wisdom." We know of no published definitive studies which show that either washing or rinsing is of any use in corrosion control; at best, it is a controversial issue. (Of incidental interest, the same may be said concerning winter-season washing of automobiles in the U.S. "salt-belt" Fig. A1.) Nevetheless, on the basis of available evidence, USAF

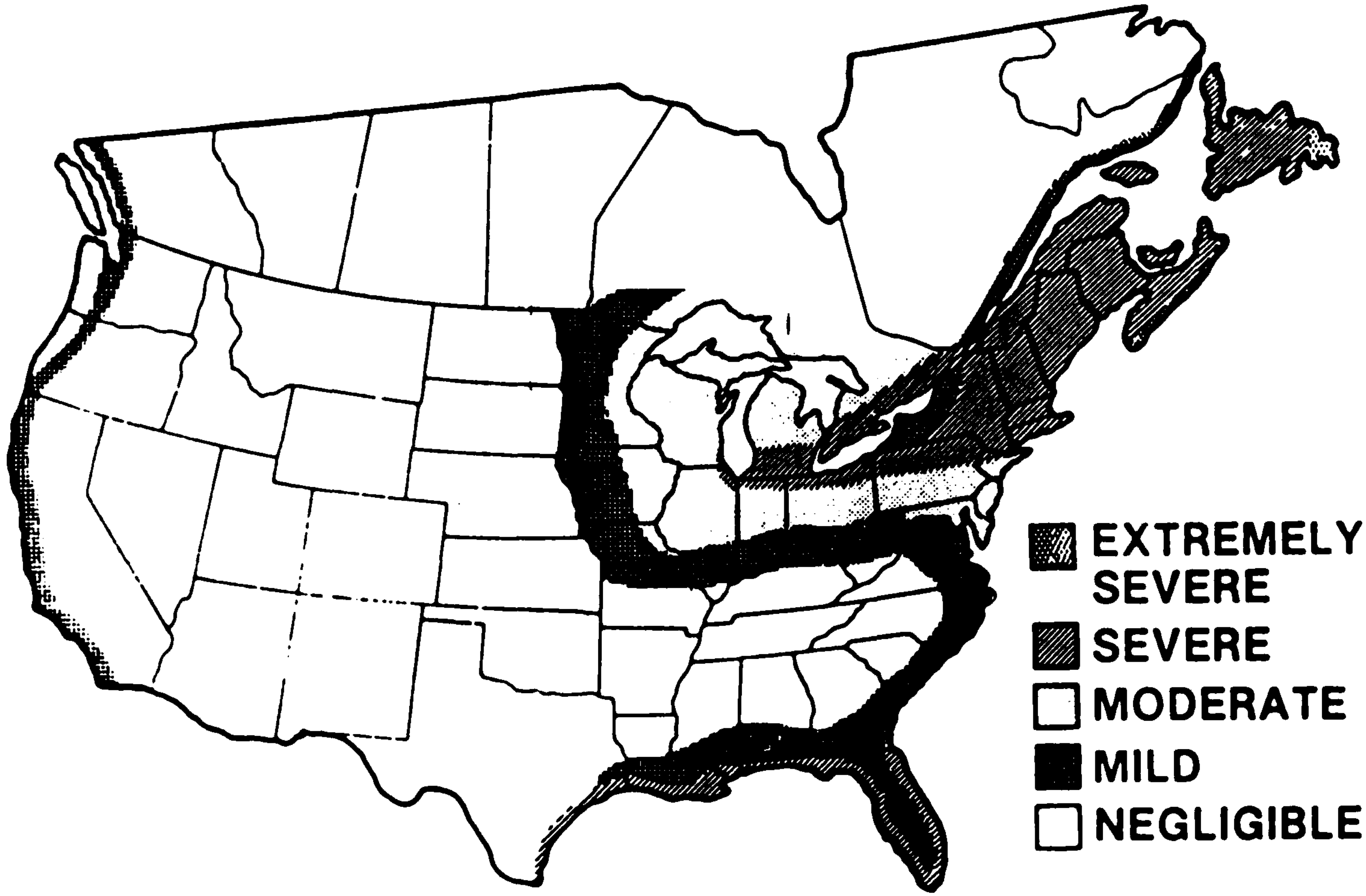

Figure 1. Salt corrosion areas of continental U.S.

Tactical Air Command and Logistics Command were persuaded that a rinse facility at MacDill could reduce overall corrosion costs for aircraft stationed there. Construction was jointly funded for FY 1977, but initial operation did not begin until 1979. Because of technical problems and incessant taxi/runway repairs, it apparently has operated only sporadically since - with and without corrosion inhibitor additives (Reference 4).

Rinsing and/or washing is intended to remove soluble deposits, particularly marine-salt, but also phosphates, sulfates (related to acid rain perhaps), nitrates, fluorides, and related solids believed or proven to be corrosive (Reference 5). At least one F-16 failure analysis at MacDill AFB implicates such substances which are known to be locally-discharged atmospheric contaminants (Reference 6). If it is conceded that these soluble deposits are harmful, then it follows that rinsing to remove them is desirable. Cost-effectiveness, however is a question which cannot be answered here. Whether rinsing does in fact remove them and whether rinsing reduces corrosion damage/costs are yet to be demonstrated.

The case against rinsing/washing has considerable support. Nuisance value must be recognized, but cannot be considered seriously. Major charges against rinsing at MacDill include:

(a) Water "drying spots" on the airplane canopy

(b) Corrosion problems on landing-gear-well electrical connectors

(c) Brake-disc fractures, caused, presumably, by cold water sprayed on hot wheels after landing.

Canopy "spotting" can be reduced or eliminated in two ways: (a) use of a surfactant additive to the rinse water and (b) "stripping" by a high velocity air stream. The second method is used in car-wash operations for just this purpose; the same result would be obtained if the airplane were rinsed preflight instead of post-flight. Note that a pre-flight rinse also eliminates the spraying of cold water onto still-hot brakes following

landing. The case for a pre-flight rinse is more convincing than is the case for a post-flight rinse.[1]

It is widely believed that salt accumulates on an airplane during low-altitude flight over salt water. Atmospheric salt concentrations decrease quite rapidly with altitude, however; typical concentrations at 100 m over open calm ocean seas are reported to be ca 0.8 to 3.6 g/m^3 of particles classed "large" and "medium," and 3 to 13 g/m^3 for "small" particles. These values compare with sea level measurements 50 m from the shore of ca 100 g/m^3, but are comparable with sea level values 1 km from shore (References 7, 8). Open sea conditions probably are not characteristic of Hillsborough Bay; 100-m altitude concentrations there probably are less than 0.5 g/m^3, corresponding to calm, sheltered waters. This writer finds it difficult to believe that an airplane flying 150-200 kt. through such an atmosphere will accumulate enough salt deposits to warrant an immediate post-landing rinse.

By contrast, ocean spray aerosols at sea level can deposit as much as 100 mg/m^2-day of sea salt on open surfaces within 1 km of the shore (Reference 9). An F-16 with 50 m^2 upper surface area thus can accumulate as much as 5 g of salt deposits per day. Airborne salt spray also will penetrate open landing gear bays, etc., although salt deposits would be less than those on exposed upper surfaces.

A variety of surfactants are available which will eliminate the problem of "drying spots." A "Calgon"-like product has been used at MacDill; whether it is the best choice is not known, but it would not be difficult to test several commercial products to find one which is compatible with the canopy and other airplane materials, and meets environmental requirements.

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1. Pre-flight rinsing has been ruled out because operational readiness requirements can not allow any delay in take-off.

Controlling surfactant concentration or that of any other rinse-water additive, however, is not a casual matter. Additives can be harmful at both excessive and insufficient concentration. Because the MacDill facility automatically replaces unrecovered rinse water with fresh water, the concentration of additives decreases with each rinse. Concentrations after each rinse can be calculated if the amount of rinse water lost per rinse is known (details of the calculation are given elsewhere in this report), although rainfall would complicate the problem somewhat. Without water consumption and true usage data, a computational method should not be used to determine when surfactant additives should be replenished.

Electrical and chemical methods can be used to monitor additive concentrations on a daily or weekly basis. A conductivity bridge was built into the MacDill system at the time of construction and was calibrated to measure the concentration of corrosion inhibitor additives. Typically, surfactant concentrations are much lower, and not all surfactants are ionic conductors, hence a conductivity bridge may not be an appropriate monitoring device. It may be possible to fit the system with different probes for electrically conductive additives and recalibrate it for lower concentrations. When this writer inspected the system (June 1984), the conductivity bridge was in a state of disrepair and nonfunctional.

It has been claimed that excessive failure rates for corroded electrical connectors and cracked brake discs have been experienced at MacDill, and it has been alleged that the fresh water rinse facility is the cause (Reference 10). No documentary evidence supports the connector failure problem. A single analysis of Work Unit Code 13E00 Brakes, etc., and How Malfunction Code 190 "cracked" covering November 1982 - October 1984, using the recently-operational "Maintenance and Operational Data Access System" (MODAS), does suggest excessive failure rates at MacDill (Reference 11). The analysis is superficial, however, and raises more questions than it answers. For example, brake disc failures apparently were highest at times when the rinse facility was not in use because of taxiway repairs. As noted elsewhere, MODAS is a powerful tool for data analysis. But statistical results should never be used without careful consideration of all relevant factors.

2. The MacDill Environment

The corrosive environment at MacDill AFB is especially severe. The air base is surrounded on three sides by the salt waters of Tampa Bay, and aircraft flight lines are as near as 500 m to the shore (Figure A-2). Eastward across Hillsborough Bay at about 7 km distance are various power generating and chemical manufacturing plants, the latter producing nitric and sulfuric acids, potash fertilizers, and others. Prevailing winds at MacDill are from the East and Northeast (Reference 12). The corrosivity of the area by now is well known (Reference 13).

The overall environmental rating of Hillsborough County as recently as 1976 was below the National Ambient Air Quality Standards (NAAQS) for particulates and SO_2 (Reference 14). Consequently, it may be argued that the region is not severely corrosive. The most aggressive environmental factor is salt, but the presence of other contaminants accelerates the effects of salt. One F-16 failure analysis has implicated a variety of contaminants peculiar to the Tampa region (Reference 6).

3. The MacDill Automatic Rinse

The facility is installed in a short taxiway. "On-off" sensors in the pavement control the 600-gal/min pump, delivering water through 31 spray nozzles set below the taxiway. The sensors are spaced 178 feet apart, hence at a taxi speed of 5 mph, the system will operate for approximately 24 sec, delivering 240 gallons of water (Reference 15).

The system uses fresh water delivered by the Tampa Water Department. This water is drawn mainly from the Hillsborough River, but when the river level is low in winter, the river water is supplemented by ground-fed springs. The spring water is high in chloride leading to January-March chloride concentrations which are an order of magnitude greater than for the rest of the year (Reference 16).

4. The Question of Inhibitors

A fresh water rinse can lead to accumulations of salt-laden water in crevices and thereby accelerate corrosion (Reference 2). If the rinse water

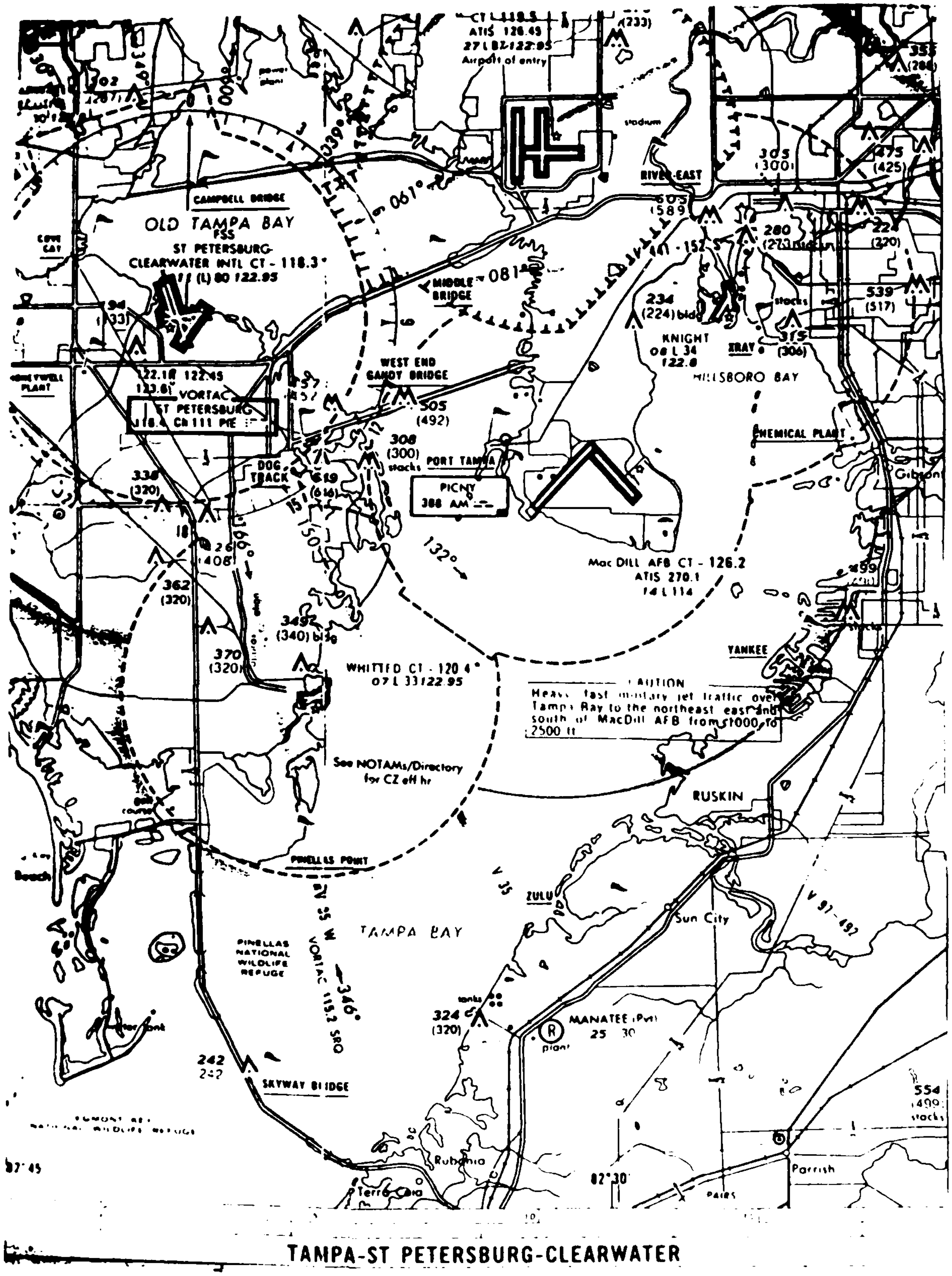

Figure 2. Map of MacDill AFB and Tampa Bay.

contained corrosion inhibitors, however, such undesirable effects might be avoided. Indeed, the collection of inhibitor-containing rinse water in "nooks and crannies" might be beneficial by providing residual corrosion protection. For this reason C.T. Lynch, formerly at AFWAL Materials Laboratory, suggested adding borax-nitrite inhibitor to the rinse water. An experimental program was started in 1978 employing a pre-mixed inhibitor formulation, corresponding to the "optimum" formulation of Khobaib (Reference 19) (Tables A-4 and A-5). The value of a fresh-water rinse was taken for granted; this program was intended to demonstrate the efficacy of adding inhibitors to such a rinse. Evaluation would be made on the basis of corrosion damage to F-4 aircraft assigned at MacDill. Unfortunately, the program fell victim to a variety of "Murphy's Laws," which have been described elsewhere (References 4, 19, 20), with the result that no definitive conclusions were possible.

This presents a formidable challenge for designing a program to test the efficacy of an inhibited rinse, of any rinse at all, or of washing airplanes in corrosion control. Past efforts have shown (References 4, 19, 21) that it is futile to attempt a classical controlled experiment (i.e., at the same air base). The "comparable case" concept, analogous to the real estate appraiser's tool, offers the best opportunity for the study, and follows the lines of eteological research.

Program

This is an experimental program which will determine whether fresh water rinsing is useful in corrosion control for aircraft in severe environments. It also will determine whether the addition of corrosion inhibitors to such rinse water is an effective corrosion control measure. The corrosion damage to selected airplanes at three air bases will be monitored for one year. Monitoring will include inspections, maintenance records, operational records, and the MacDill rinse facility. The program requires virtually no participation of operational or field commands, the only exception relating to inspections. There will be no impact on TAC operations Fig. A-3).

Table 4. Recommended Inhibitor Concentrations, Weight Per Cent

	"Optimum"[19]	Erny Supply[20]
Borax	0.35	.244
Sodium Nitrate	0.1	.153
Sodium Nitrite	0.05	.075
Silicate	0.01	.007
Phosphate	0.002	.004
MBT	0.001	.007
Sum	0.513	0.48

Table 5. Inhibitor Formulation used MacDill, 1978

		Formula Weight	Erny Makeup[20]
Borax	$Na_2B_4O_7 \cdot 10H_2O$	381.37	535 lbs.
Sodium Nitrate	$NaNO_3$	84.80	335
Sodium Nitrite	$NaNO_2$	69.00	165
Sodium Metasilicate Pentahydrate	$Na_2SiO_3 \cdot 5H_2O$	212.74	16.5
Sodium Hexameta Phosphate	$(NaPO_3)_xNa_2O$		3.5
MBT, Mercapto-benzothiazole		167.25	1.5
			1056

Essentially, the study is accepted to be uncontrolled and is similar to the analysis of time series in economics and the social sciences or in etiology, where the analyst can only observe, with no opportunity to control the events, the results are said to be non-experimental.

We make use of the real estate agent's phase "comparable case." For our purposes, the comparables (Table A-6) are:

- MacDill AFB, having a humid, salt water environment and a sporadically-used rinse facility.
- Hill AFB, Utah also having a salt water environment, less severe, but having no rinse facility and presumably no practice of fresh water rinsing.
- Shaw AFB, South Carolina, having a less humid environment, no nearby salt sources, no rinse facility, and no particular reason to rinse airplanes.

Comparing airplane condition and maintenance costs at these three air bases cannot be described as an ideal experiment. Their environments differ in a variety of factors, the nature and effects of which have been discussed extensively elsewhere (Reference 5). Nevertheless it should be possible to separate the effects of such factors and demonstrate whether rinsing has any good or bad impact on corrosion.

Selected airplanes, four at each air base, are to be inspected at the start, middle, and end of the program. The airplanes to be inspected will be selected according to statistical principles described elsewhere (Reference 21). Inspections will be made at 200-hour phase inspections or at Programmed Depot Maintenance. Four inspectors are required. The inspection points will number ten or less, pre-selected from analysis of maintenance data, previous corrosion control inspections, and materials properties.

Airplane condition will be monitored in addition via the Maintenance Data Collection System (MDCS, AFR 66-1) and the Maintenance and Operational Data Access System (MODAS). A variety of ancillary data have been collected for cross-reference purposes, including aircraft inventory and statistics, and weekly/monthly flight and maintenance schedules at MacDill AFB.

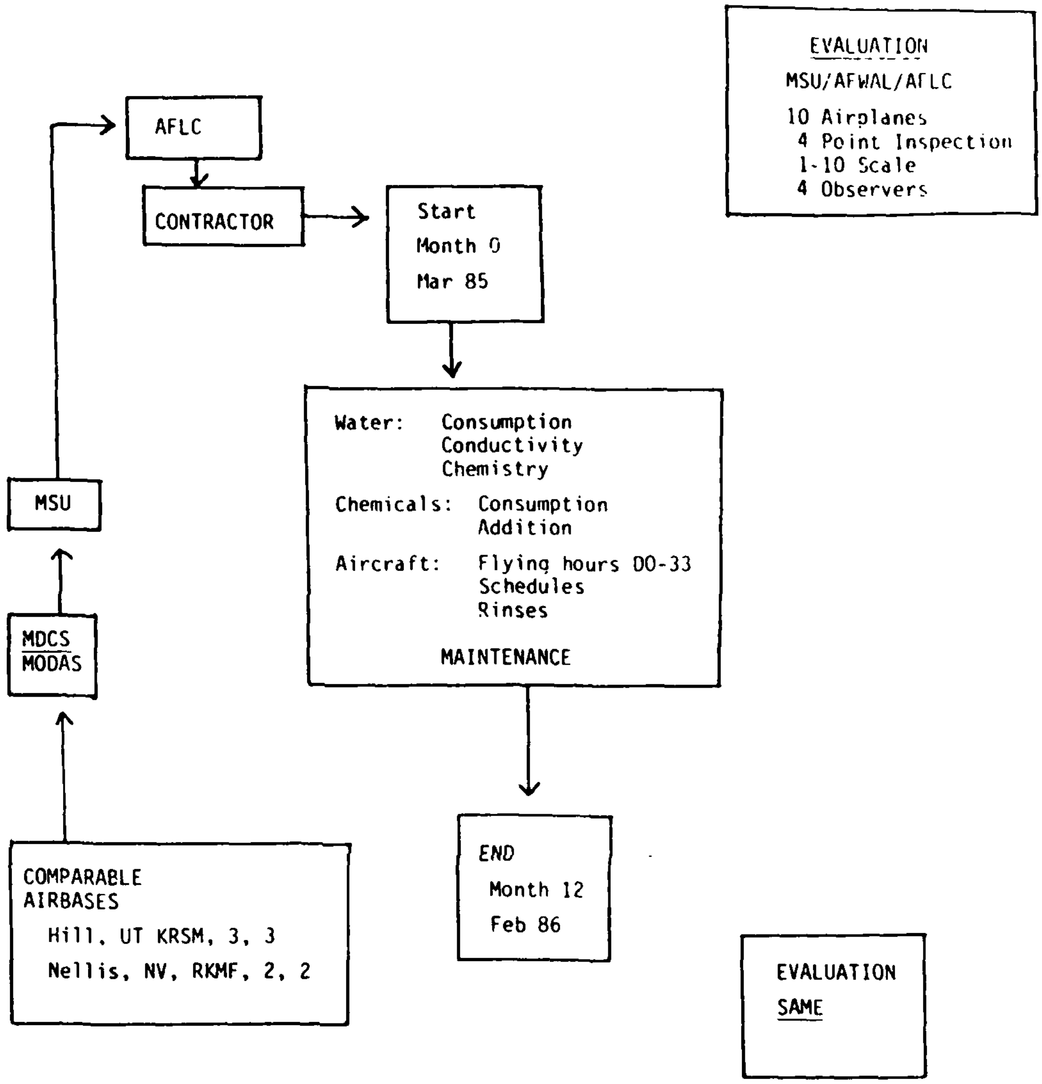

Figure A-3. Evaluation of Fresh Water Rinse and Corrosion Inhibitors Additives - schematic.

Table 6.

F-16 Assignments and Inventories as of 17 August 1984

Airbase	Code [a]	PACER LIME Rating	Inventory	Mean Age, Yrs.	Oldest/ Newest, Yrs.	Mean Air-Frame Hrs.
Hill, Utah	(KRSM)	3, 3	106	1.3	4.9/0.3	383
Luke, Arizona	(NUEX)	3, 2	57	4.9	6.0/3.9	1082
MacDill, Florida	(NVZR)	4, 4	86	3.7	4.6/2.7	907
Nellis, Nevada	(RKMF)	2, 2	113	2.8	3.8/0.8	827
Shaw, S. Carolina	(VLSB)	3, 2	53	1.5	3.8/0.2	434
Mean CONUS		3, 2.6	425	2.7	6.0/0.4	706
Hahn, Germany	(JWEC)	2	79	2.2	2.7/0.7	527
Kunsan, Korea	(MLWR)	4	53	2.1	2.7/1.0	551
Torrejon, Spain	(XGBX)	3	79	0.7	1.6/0.1	343
Mean, H-K-T		3	164	1.4	2.7/0.1	343

a. AFR 300-4, Volume XII

Effective conduct of the program requires continuous on-site monitoring of a variety of details, including

- Water meter readings
- Chemical Analysis of the rinse water
- Additive replenishment as required
- Usage of the facility by aircraft
- Repair whenever inevitable breakdowns occur.

Ordinarily these tasks might be assigned to regular air base personnel, either civilian or military. Such personnel have effectively conducted one-time special inspection requests (SIR), the use of which is a routine practice for airframe manufacturers to explore potential problems in operational systems (Reference 22). Unfortunately, this approach to field-level studies has proved invariably to be nearly worthless when the tasks span extended time intervals (References 4, 19, 21, 230. Moreover, the value of field-level data in its most widely used form, the Maintenance Data Collection System (MDCS), has been seriously challenged (References 21, 24).

The reasons why field personnel have failed to perform such tasks satisfactorily are well-known and have been discussed widely:

1) It is not their primary mission.
2) They have not received adequate training
3) Frequent personnel transfers and vacations break program continuity.
4) There are pressures to attend to other tasks first.
5) Poor attitude concerning the project.
6) Untimely redeployment of equipment in the middle of study.

There are, of course, other factors. Regardless of the reasons, it is not likely that the desired results can be obtained through the efforts of USAF personnel. The work must be assigned to a local contractor-preferably academic, e.g., University of South Florida.

Our program has been tailored carefully to counter most of the known experimental hazards.

1) It will span the shortest feasible time, viz., one year.
2) Personnel complications are minimized.
3) Suitable controls are provided, including

a) flight schedule monitoring _via_ weekly and monthly schedules,
b) maintenance monitoring _via_ MODAS, monthly maintenance reports, DO-56 Product Reports,
c) comparison with other air bases,
d) careful tracking of selected airplane serial numbers which will not be revealed to base personnel, and
e) inspection of selected airplanes by an appropriate 4-person team at 200-hour Phase inspections.

Statistical experimental design is a central feature of the program.

Water Analysis

Rinse water samples from the rinse source tank will be analyzed not less than daily, preferably twice daily. In the initial six-month period when corrosion inhibitors are _not_ used, parameters analyzed will include only chloride ion and pH. When corrosion inhibitors are used in the second six-month period, analysis will include also nitrate and nitrite ion concentrations. Standard analytical test methods and reagents are available at low cost (Reference 25). Acidity can be determined by wet chemical or electronic methods, the latter being preferable, but requiring a special low-cost instrument. In conjunction with our laboratory studies, we have initiated a program to evaluate inhibitor concentrations before and after corrosion testing.

Chloride Accumulation in the Rinse System.

The upper surface area of an F-16 is approximately 50 m^2. Assuming that the maximum rate of salt deposits is 100 mg/m^2-day, then rinsing one airplane would dissolve 5 g of salt as a "worst case" example. Perhaps 1 g would not return to the storage tank with unrecovered rinse water, hence the salt content of the stored water would increase by _ca_ 4 g per aircraft rinse.

The capacity of the system is _ca_ 3000 gal (Reference 15). Since normal finished Tampa City water contains 15-30 mg/l NaCl (Reference 17), the water holding tanks filled with fresh water contain about 350 g. Thus an aircraft rinse will increase the initial salt concentration by about one

per cent. Although the increment per rinse is negligible, the salt concentration could become significant over extended time intervals.

Additive Depletion

Rinse water is not recovered completely because of evaporation, carry-through, and runoff. We have only "guestimates" of the fraction recovered ranging from 25 to 75%; although an accurate value could be obtained, from daily water meter readings and frequency-of-use data. Unrecovered rinse water also carries with it additives and inhibitors, thus diluting their concentrations for the next rinse because lost water automatically is replaced with fresh water. When the minimum effective concentration is reached, the additive should be replenished.

The additive concentration, c_n, after a number of rinses, n, can be calculated from the initial concentration c_o and the amount of water lost per rinse. Lost water is the fraction x of water used. Since the system delivers 600 gal per minute, an airplane taxing at 5 mph through the 178-foot rinse area would draw a = 240 gal in 24 sec. Thus,

$$d_n = \left(\frac{b-xa}{b}\right)^n c_o,$$

where b is the water capacity of the system, (3000 gal or 11300 kg); units are appropriate to the concentration expression, i.e., mass per volume or weight per cent.

For example, if the fraction of water lost is x = 0.25, then after ten rinses,

$$C_{10} = 0.817\ C_o,$$

and after 100 rinses,

$$C_{100} = 0.133\ C_o.$$

We also may calculate the amount of additive lost after n rinses from

$$(C_n - C_o)\ b$$

Thus, after 100 rinses - a typical MacDill week (Reference 26) - the "optimum" inhibitor formulation (Reference 19) would have been depleted by 110 lb, from an initial charge of 120 lb, based on 25% water loss.

It may be noted that when inhibitors were added to the MacDill facility, the initial charge was three 40-lb pails. Weekly replenishment was at the rate of one 40-lb pail, determined from the conductivity bridge measurement, suggesting water losses may be somewhat less that 25% (Reference 26).

5. Maintenance and Operational Data Access System (MODAS)

MODAS is an interactive data base management system containing the most-recent 24 months of reported field- and depot-level operational and maintenance data. It is accessible via public data networks until the Defense Data Network becomes operational.

The system permits the analyst to study and extract such data in ways not previously possible. Earlier data analyses could be performed only batchwise in much narrower and rigidly defined scope.

MSU will use MODAS to analyze the condition of F-16 airplanes at the three air bases prior to initiation of this program as well as through its duration and subsequently. Although MODAS contains powerful internal analysis routines, data will also be extracted and analyzed using a variety of techniques developed in earlier research.

6. Discussion

The rinsing of airplanes is both expensive and controversial. Rinsing advocates argue that it is an effective tool in corrosion control. Detractors argue that it does more harm than good. Neither opinion is supported by sound technical evidence. Nevertheless, there is considerable demand costly automatic rinse facilities.

The program outlined here will demonstrate the effects of rinsing, whether positive or negative, as well as the value of adding corrosion inhibitors to the rinse. Its costs and time span are minimal, and it will have no impact on MacDill operations. From the program results, AFLC and

others will have the information needed in order to make decisions of whether, where, when, and how a aircraft shall be rinsed.

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APPENDIX B.

PACER LIME: Environmental Corrosivity - Non-CONUS Air bases

Robert Summitt and Kenneth B. Lenz
Metallurgy, Mechanics, and Materials Science
Michigan State University
East Lansing, Michigan 48824

February 1985

Interim Technical Report

for Period 1 April 1984-28 February 1985

1. Introduction

The PACER LIME system for classifying environmental corrosivity (Reference 1) was developed in response to Strategic Air Command (SAC) needs for planning corrosion maintenance for airplanes deployed in widely diverse environments. AF Logistics Command (AFLC) started the program in 1965 with two objectives:

(1) To develop an algorithm which computes a priori environmental ratings from weather and other ambient factors;

(2) To "calibrate" such ratings via field testing of selected aircraft alloys.

Interim severity classifications were calculated from a "first-cut" corrosion factor equation and distributed within USAF in 1972, 1973, and 1974 (Reference 2[1]). Simultaneously, a field test program was effected for the purpose of providing experimental data to be compared with the interim classifications (Reference 3).

By 1978, the program had grown beyond the available internal resources of AFLC, and it was transferred under contract to Michigan State University (MSU). MSU analyzed experimental results of the field test, the interim "Base Corrosion Severity Classification System," and developed an improved classification system.

This system has two central features.

1. Threshold values for known environmental corrodents, established from statistical analysis (Reference 4) of observed environmental factors (References 5, 6); these were termed Working Environmental Corrosion Standards (WECS).
2. Algorithms which compare the air base environment with WECS, beginning with the most corrosive factors to the least, resulting in a severity classification.

The essentials of this system are reproduced from Reference 1. Classifications were computed from this system for all CONUS air bases as

1. Discussion of this effort is published only in References 1 and 3.

well as a number of well-documented field-test sites. These were compared with published experimental field test results and with USAF corrosion maintenance experience documented in the AFR 66-1 Maintenance Data Collection System (Reference 7). The correlation between predicted severity and actual damage was sufficiently good, that the classifications could be adopted by AFLC.

Subsequently, a number of problems related to the recommendations have surfaced. Some are the subject of current research, but two are discussed here.

1. The algorithms were designed to be simple so that air base-level personnel could evaluate local conditions from locally-measured or locally available factors. Base-level personnel have proved reluctant to exercise such discretion; one would wish for similar reluctance with respect to field-level painting.
2. Washing interval recommendations (30-60-120 days) for relative severities were presented as illustrations based upon the then-current practices for various aircraft systems. It was implicit, but unfortunately not explictly stated, in our report that minimum/maximum washing intervals would be determined by AFLC, and determination of local intervals would take account of base-peculiar conditions, e.g., severe prolonged winters or the availability of a daily-used rinse facility. The example values (30-60-120 days) were adopted, however, and there is wide sentiment that these may not be the most effective choices.

Under a current AFWAL contract, MSU addresses three PACER LIME-related questions:

(1) Are the fundamental P-L assumptions concerning environmental factors and their intensity reflected in more recent maintenance and field test data? Essentially, this is an updated comparison of algorithm ratings with newer data, particularly those related to pollutants (References 8, 9).

(2) Is the air base environment significantly different from that reflected in EPA-type pollutant data measured at the nearest reporting site? Comparison of more comprehensive data in

selected areas and data collected on-air base may provide answers.

(3) Ratings for non-CONUS air bases were not computed in Reference 1, because the necessary environmental information was much less accessible, and remains so. Non-CONUS ratings are required.

This Report deals with third question. Through the efforts of C.J. Robinson, Warner-Robbins ALC, and Mr. K. Lenz, MSU, data have been collected for overseas air base locations and they have been processed into a form useable with the PACER LIME algorithms. The data are included here, with a discussion of the collection process and the resulting air base corrosivity ratings. Also included, as an Appendix, are corrosivity ratings calculated for US Army bases in CONUS by F. Fink.

It is expected that the PACER LIME algorithms will be revised as the first two questions are answered, consequently local corrosivity ratings are subject to revision but dramatic changes are not anticipated. Moreover, both CONUS (Reference 1) and non-CONUS ratings are based on the best available data. If users of this report have access to better environmental data, they are urged to compute their own local ratings and to communicate their information to the authors.

2. Environmental Corrosive Factors (Reference 1)

A thorough review of the literature of corrosion and environment resulted in the following conclusions.

1. Environmental factors known to be corrosive and widely distributed are relatively few in number.
2. The concentration or intensity of these common factors is monitored extensively by weather and environmental agencies, at least within the CONUS, and to a limited extent worldwide.
3. The corrosivities of such factors are proportional, although not necessarily linearly proportional, to their individual intensities. Further, there will be a critical, or threshold intensity for each factor, above which that factor will significantly degrade the environmental corrosivity.

4. Such threshold values necessarily are within the statistical limits ambient in the CONUS, because it already is acknowleded that existing environments span the range from non-corrosive to severely corrosive.
5. Environmental factors must be evaluated as a locally-unique combination, recognizing the possibility o f synergistic effects among them.

These conclusions resulted in two postulates concerning environmental corrosivities.

1. Severity thresholds for any corrosive environmental factor can be determined (or at least estimated) from statistical analysis of ambient observations.
2. <u>Local</u> environmental severity can be evaluated by considering the intensity of each factor in turn, in its order of relative severity, compared with the above-determined threshold values, thus producing a synergistic combination of the peculiar local combination of factors.

A widely-quoted analysis of weather and pollutant data from 1976 (Reference 4) provided the basis for "Working Environmental Corrosivity Standards" (WECS) used in Reference 1. These WECS are reproduced in Table B-1. From a comprehensive evaluation of the corrosivity and intensity of environmental factors, three algorithms were developed which combine local ambient factors and result in

a. recommended aircraft washing intervals;
b. repainting intervals; and
c. corrosion damage estimates.

TABLE B-1. Working Environmental Corrosion Standards (WECS)

Ambient Factors	Annual mean I	Annual mean II
Suspended particulates ($\mu g/m^3$)	61	86
Sulfur dioxide ($\mu g/m^3$)	43	72
Ozone ($\mu g/m^3$)	36	47
Nitrogen dioxide ($\mu g/m^3$)	64	78
Absolute humidity (g/m^3)[a]	7.1	9.0
Proximity to sea or salt source (km)	4.5	2
Solar radiation, July (Langleys)	600	650
Rainfall (cm total)	125	150

[a] Absolute humidity is the product of relative humidty and the mass of water in one cubic meter of water-saturated air at a given temperature.

Time interval recommendations of (a) and (b) were intended to be comparative values, and were illustrated as 30-60-120 days for washing, whereas repaint intervals were based upon the probable lifetime of coatings systems. Corrosion damage estimates were intended to be the basis for maintenance scheduling and related logistics decisions and to be incorporated within the Reliability-Centered Maintenance Program (Reference 10). The aircraft washing algorithm (AWA) and the corrosion damage algorithm (CDA) are reproduced in Figures B-1 and B-2, and were used to evaluate the non-CONUS air base environments below. The aircraft repaint algorithm (ARA) is not discussed here, because the necessary environmental data could not be acquired. Moreover, the relation between "paint" and corrosion invariably is confounded by the frivolous proclivity of field commands to repaint aircraft.

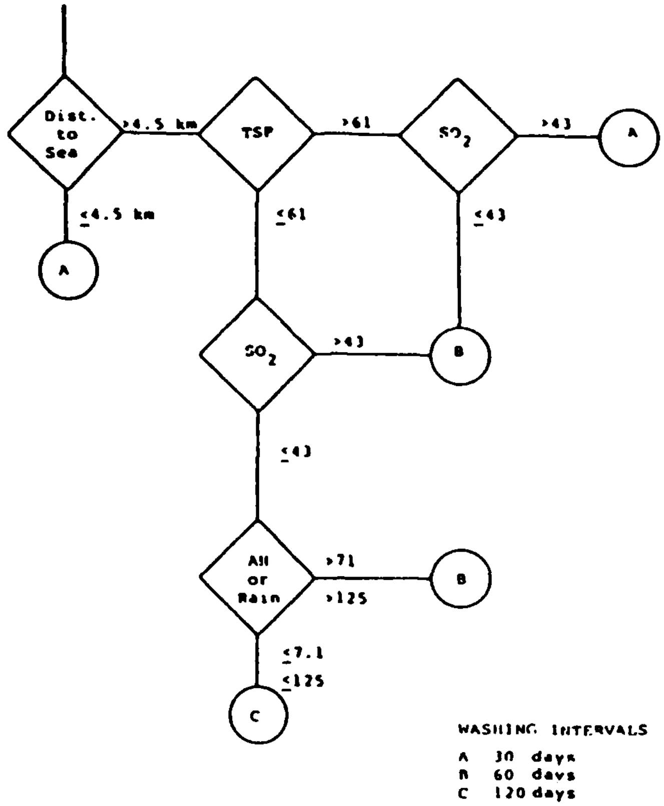

Figure B-1. Aircraft Washing Interval Algorithm. Working Environmental Corrosion Standards I (see Table B-1) are used. Units for TSP, and SO_2 are $\mu g/m^3$, and for rainfall, annual total cm.

The Corrosion Damage Algorithm was compared in detail with field test data for aerospace alloys and with operational maintenance costs from two USAF airplane systems (C-141A and B-52 series). In both comparisons, sufficiently good agreement was found between predicted and actual corrosion damage, that all three algorithms were recommended to USAF as the initial basis for environmental classifications.

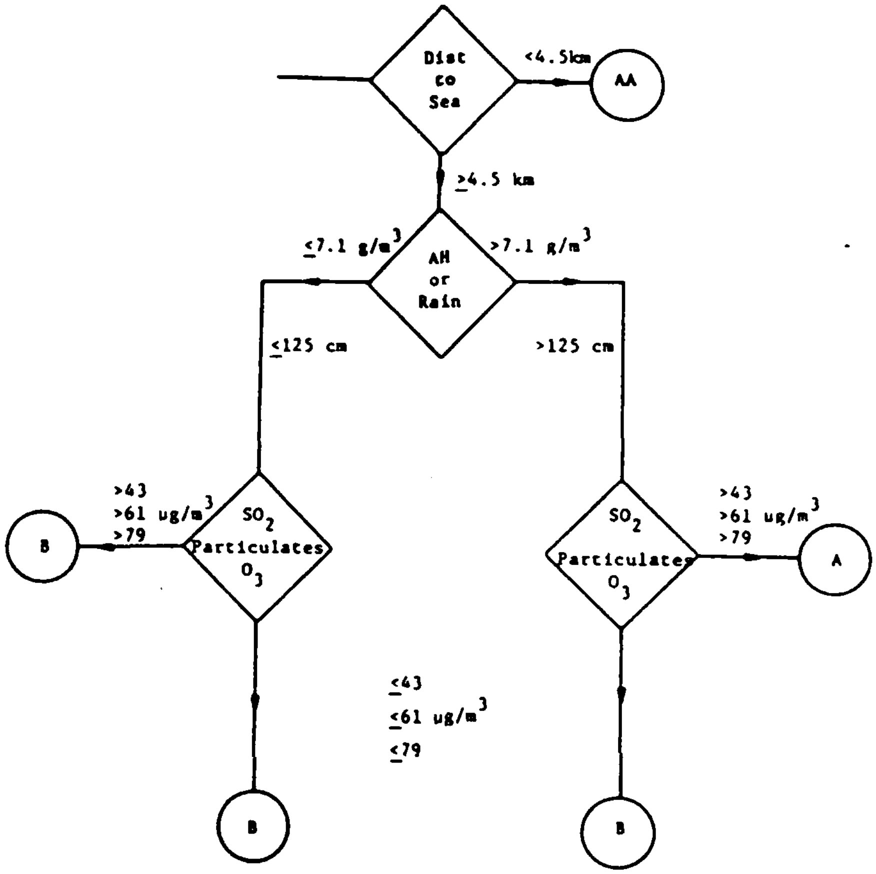

Figure B-2. Corrosion Damage Algorithm for Aircraft using set I of Working Environmental Corrosion Standards (Table B-1).

3. <u>Environmental Data</u>

The PACER LIME algorithms are based upon data in a specific format, because they were derived from environmental studies performed in the CONUS. These data are divided into two categories: (a) climatologic or weather factors; and (b) atmospheric contaminants. Several agencies collect and publish this data for CONUS. In the PACER LIME study, weather factors were taken from USAF Environmental Technical Applications Center (ETAC) compilations (Reference 11), and contaminant data from U.S. Environmental

Protection Agency publications (Reference 12). ETAC data span the entire globe, hence may be used for non-CONUS air bases. Unfortunately, pollutants are not monitored elsewhere in the world in the same ways and with the same enthusiasm as they are in the United States. Consequently, application of the PACER LIME algorithms to non-CONUS locations is neither simple nor straightforward.[2]

It is not suggested, of course, that non-US scientists and engineers do not study atmospheric pollutants. The literature is rich with data, and very detailed studies have been published, especially for Europe and the Soviet Union (References 13, 14). The problem stems from the fact that no single agency, like the U.S. Environmental Protection Agency, functions as a central "clearing house" for compiling and publishing data in a standard format. Under sponsorship by the World Health Organization (References 13-16), programs are in progress to correct this situation. Currently, however, data simply are "hard to come by."

Because of numerous requests from non-CONUS air bases for environmental ratings, Warner-Robins ALC attempted (mightily) to collect the data required to apply the PACER LIME algorithms. In December 1983, Miss Karrie Jo Robinson, W-R/ALC, contected the U.S. Embassy Science Counselor in each U.S. air base host country requesting local environmental data. In addition, she requested assistance from ETAC in February 1984. She received excellent data compilations from Korea and Spain, and useful material from the U.K.; no useful information was received from other countries. In late summer of 1984, we learned of these efforts and requested (and received) copies of the material. At the same time, Mr. Lenz was tasked with collection and formatting of worldwide environmental data into a form suitable for the PACER LIME algorithms. The principal sources are References 17-20. We are continuing our effort to compile and computerize environmental factors and corrosion damage data (Reference 21).

From a careful evaluation of the available data compiled as above, environmental factors useable in the PACER LIME algorithms have been

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2. As a matter of fact, this also is true for CONUS locations.

Table B-2. Non-CONUS Airbase Data and Environmental Corrosivity Ratings for Aircraft Washing and Corrosion Damage

Air Base	Country	Latitude [a]	Longitude [a]	TSP [b]	SO_2 [b]	NO_x [b]	Temperature [c]	Absolute Humidity [d]	Rainfall [e]	Distance to Sea, km	Wash Interval	Corrosion Damage
Alconbury	UK	05222N	0013W	78	75	75	9.4	7.0	53	85	A	B
Aviano	Italy	04602N	01236E	73	185		12.5	8.0	150	55	A	A
Bentwaters	UK	05208N	0126E	61	91	75	9.7	7.6	55	7.0	B	A
Bitburg	W. Germany	04957N	0634E	70	55		8.3	6.6	63	270	A	B
Camp New Amsterdam	Netherlands	05210N	0503E	65	91		9.4	7.3	77	17	A	A
Clark	Phillipines	01511N	12033E	76	82		26.9	18.8	173	25	A	A
Hahn	W. Germany	04957N	0716E	70	55		7.8	6.6	74	325	A	B
Hellenikon	Greece	03754N	02344E	215	30		17.7	9.7	40	8	B	A
Howard	Canal Zone	0855N	07936W	45	12	28	20.5	13.7	254	16	B	B
Incirlik	Turkey	03700N	03526E	assumed low	assumed low		19.2	10.2	65	43	B	B
Izmir	Turkey	03818N	02701E				16.9	9.0	52	4	A	AA
Kadena	Japan	02621N	12746E	assumed low	assumed low		22.5	15.3	317	1.5	A	AA
Kelflavik	Iceland	06359N	02236W		40		5.0	5.5	115	1.0	A	AA
Kunsan	S. Korea	03554N	12637E		36		12.8	8.8	119	3.0	A	AA

Table B2 con't

Air Base	Country	Latitude [a]	Longitude [a]	TSP [b]	SO_2 [b]	NO_x [b]	Temperature [c]	Absolute Humidity [d]	Rainfall [e]	Distance to Sea, km	Wash Interval	Corrosion Damage
Lajes Field	Azores	03846N	02706W	assumed low	assumed low	assumed low				<1.0	A	AA
Lakenheath	UK	05224N	0034E	78	75	75	9.4	7.1	54	80	A	B
Mildenhall	UK	05222N	0029E	78	75	75	9.4	7.1	54	80	A	B
Osan	S. Korea	03705N	12702E		31		11.7	7.9	135	18	B	B
Ramstein	W. Germany	04926N	0736E	80	60		8.3	6.7	62	370	A	B
Rhein-Main	W. Germany	05002N	0834E	135	145		9.4	6.9	67	395	A	B
Sembach	W. Germany	04930N	0752E	80	60		8.3	6.5	66	385	A	B
Spangdahlem	W. Germany	04959N	0642E	70	55		8.0	6.5	67	275	A	B
Taegu	S. Korea	03553N	12840E		71		13.7	9.2	120	60	A	A
Torrejon	Spain	04029N	0327W	169	79		13.9	7.6	41	390	A	A
Upper Heyford	UK	05156N	0115W	78	75	75	9.2	7.2	59	93	A	A
Woodbridge	UK	05205N	0124E	61	91	75	9.7	7.5	62	12	B	A
Yakota	Japan	03545N	13921E	52	46		14.2	9.3	158	45	B	B
Zaragoza	Spain	04140N	0102W	31	64		14.4	8.2	31	183	B	A
Zweibrucken	W. Germany	04913N	0724E	80	60		9.2	7.0	82	375	A	B

Footnotes:

a. Latitude and longitude are in degrees and minutes, e.g., 05222N is 52^{o} 22' N, where the last two digits are minutes.

b. Atmospheric contaminants are mean annual values in micrograms per cubic meter.

c. Mean annual temperature, degrees Celcius.

d. Absolute humidity is the product of mean annual relative humidity times the mass of water, grams per cubic meter, in water-saturated air at the mean annual temperature.

e. Mean annual rainfall, centimeters.

determined. These, together with resulting air base corrosivity ratings, are listed in Table B-2. (CONUS U.S. Army base ratings also are in Appendix A.)

4. Conclusions

PACER LIME is an advanced approach to describing environmental corrosivity. It is a "quantum-step" advance beyond the "rural-urban-marine-industrial" classification method in use for the past few decades. The only alternative approach, viz., mapping environmental severity (Reference 22), is utterly worthless for evaluating extremely localized environments such as at an air base.

PACER LIME, it its present form still is evolutionary, and requires much "fine-tuning." This fine-tuning will consists of field-level experience feed-back, maintenance data analysis, and improved environmental parameters. Readers of this report are invited and encouraged to write to the senior author with their views and opinions, whether critical or (hopefully) complimentary.

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Appendix 1. Environmental Corrosivity - U.S. Army CONUS Bases.

MICHIGAN STATE UNIVERSITY

COLLEGE OF ENGINEERING • DEPARTMENT OF METALLURGY
MECHANICS AND MATERIALS SCIENCE

EAST LANSING • MICHIGAN • 48824-1226

MEMORANDUM

TO: Professor Robert Summitt

FROM: F.T. Fink Fred

DATE: February 7, 1985

SUBJECT: Environmental Corrosion Severity Classifications for Several U.S. Army Bases

Attached is a set of corrosion severity classifications which were developed using the PACER LIME algorithms which you designed for the Air Force. Threshold valves used were identical to those suggested in your Working Environmental Corrosion Standards.

Some of the atmospheric data used in the calculation of these classifications is badly out-of-date. New calculations will be based on more recent data.

If a precise base location was not available, indices were calculated based on the most severe concentrations of atmospheric pollutants reported by the EPA for the general base vicinity.

The classifications reported here have not been compared to independently collected corrosion data for Army bases.

You may include a copy of these classifications in your Air Force report if you wish.

FTK/ajk

U.S. BLACKHAWK SITES LISTED BY STATE

POST	REPAINT	CORROSION SEVERITY
Alabama		
Montogomery	CC	BB
Birmingham	BB	AA
Anniston	CC	BB
Redstone Arsenal, Huntsville	BB	AA
Ft. Rucker, Daleville	BB	AA
Ft. McClellan, Anniston	BB	AA
Alaska		
Ft. Greely	CC	AB
Ft. Richardson	CC	AB
Ft. Wainwright	CC	AA
Fairbanks	CC	AA
Arizona		
Davis Monthan, Tuscon	BC	AA
Ft. Huachuca, Sierra Vista	BC	AB
Yuma P.G.	BC	AA
Arkansas		
Little Rock	CC	AB
California		
Ft. Ord, Monterey	BB	AA B
Ft. Baker, Sausalito	BB	AB
Sharpe AD, Lathrop	BB	AA
Moffet Field	BB	AB
Chula Vista	AB	AA
Los Angeles	AB	AA
San Francisco	BB	AA AA
Fresno National Guard	AA	AA
China Lake NAS	BB	BB
Culver City	BB	AA
Patton USARC, Bell	BB	BB
Los Alamitos	AB	AA
Sierra AD, Herlong	BB	AB
Hamilton AFB, San Rafael	AA	BB
Edwards AFB	BB	BB
Mountain View		
Colorado		
Ft. Carson, Colorado Springs	BC	AA
Denver	BB	AA
Fitzsimmons MED, Denver	BB	AA
Connecticut		
W. Hartford	BB	AA
Bridgeport	CC	AA AA
Bloomfield	BB	AB

II-1

Delaware

No Posts

District of Columbia

No Posts

Florida		
MacDill AFB, Tampa	AB	AA
Orlando	CC	BB
Hollywood	AA	AB
Tampa	CC	AA AA
Homestead AFB	CC	AA B
Stuart	AB	AA A
NAS Penscola	BB	AA AA
Georgia		
Ft. Benning, Columbus	CC	BB
Ft. Stewart, Hinesville	CC	AB
Hunter AAF	CC	AB
Ft. Gordon, Grovetown	CC	AB
Ft. McPherson, Atlanta	CC	BB
Dobbins AFB, Marietta	CC	BB
Hawaii		
Barbers Pt. NAS	CC	AA AA
Schofield Brks.	CC	AA AA
Idaho		
No Posts		
Illinois		
Rock Island Arsenal	CC	AB
Cahokia	CC	AB
Chicago	CC	AA
Ft. Sheridon, Highwood	CC	BB
Glenview NAS	CC	AA
Scott AFB	BB	AA
Bi-State Apt., Cahokia	CC	AB
Indiana		
Ft. Benjamin Harrison	BB	AA
Indianapolis	BB	AA
Iowa		
Des Moines	CC	AA
Kansas		
Ft. Leavenworth	BB	AA
Witchita	CC	AB
Ft. Riley, Junction City	CC	AB
Olathe	CC	AC

Kentucky		
Ft. Campbell, Hopkinsville	CC	BB
Louisville	AA	AA
Ft. Knox	BB	AA
Louisiana		
Ft. Polk, Leesville	CC	BB
New Orleans	BB	AA A
New Iberia	BB	AA
Baton Rouge	CC	BB
Maine		
No Posts		
Maryland		
Gaithersburg	BB	AA
Ft. Meade, Laurel	BB	AA
Patuxent	BB	AA
Aberdeen P.G.	BB	AA
Massachusetts		
Boston	BC	AA AA
Brockton	AB	AA A
Ft. Devens, Ayer	CC	BB
Michigan		
Detroit	CC	AB
Livonia	CC	AB
Warren	CC	AB
Minnesota		
Ft. Snelling, St. Paul	CC	AA
Mississippi		
Pascagoula	AB	AA
Vicksburg	CC	BB
Missouri		
St. Louis	CC	AB
Ft. Leonard Wood	BB	AA
Montana		
No Posts		
Nebraska		
No Posts		
Nevada		
Las Vegas	CC	AA
New Hampshire		
Cold Weather RS, Hanover	AB	AA

<u>New Jersey</u>			
Ft. Dix, Wrightstown	CC	BB	
Lakehurst N.A.S.	CC	BB	
Dover	CC	BB	
Camden	CC	BB	
Edison	CC	AB	
Ft. Monmouth, Oceanport	CC	AA	AA
Pedricktown	CC	AB	
<u>New Mexico</u>			
White Sands, Las Cruses	AA	AA	
<u>New York</u>			
Syracuse	BB	AA	
Watervliet Arsenal	BB	AA	
West Point	BB	AB	
Buffalo	BB	AA	
New York	CC	AA	AA
Liverpool	CC	AB	
St. Wadsworth	CC	AB	
Stewart Airfield, Newburgh	CC	AB	
Ft. Tilden	BB	AA	
Ft. Totten, Flushing	BC	AA	
Rochester	CC	AB	
Hempstead	CC	BB	
Ft. Drum	BC	AB	
<u>North Carolina</u>			
Charlotte	CC	BB	
Ft. Bragg, Fayetteville	CC	AB	
<u>North Dakota</u>			
No Posts			
<u>Ohio</u>			
Cleveland	BB	AA	
Columbus	BB	AA	
<u>Oklahoma</u>			
Norman	CC	BB	
Oklahoma City	CC	BB	
Ft. Sill, Lawton	CC	AB	
<u>Oregon</u>			
No Posts			
<u>Pennsylvania</u>			
Pittsburgh	BC	AA	
Letterkenny A.D., Culburtson	BC	AB	
Oakdale	BB	AA	
Willow Grove N.A.S.	BB	AA	
Johnstown	BB	AA	
Greencastle	BB	AA	
Horsham	BB	AB	
New Cumberland	BC	AA	

Pennsylvania (cont.)		
Indiantown GAP	BB	AB
Carlisle Brks	BB	AB
Morton	BB	AB
Allison Park	BB	AB
Rhode Island		
No Posts		
South Carolina		
Ft. Jackson, Columbia	CC	AB
South Dakota		
No Posts		
Tennessee		
No Posts		
Texas		
Grand Prairie	BB	AB
Ft. Worth	AA	AA
Houston	BB	AA
Tomball	BB	AB
Ft. Bliss, El Paso	AA	AA
Kelly AFB, San Antonio	BC	AB
Corpus Christi, N.A.S.	BC	AA AA
Red River A.D., Texarkana	BC	AB
El Paso	BC	AB
Addison	BC	AB
Garland	AB	AA
Amarillo	BB	AA
Ft. Sam Houston, San Antonio	BC	AB
Ft. Hood, Kileen	AB	AA
Bryan	BC	AB
Utah		
Ft. Douglas, Salt Lake City	BC	AA
Dugway P.G.	BC	AA
Vermont		
No Posts		
Virginia		
Ft. Belvoir, Newington	CC	AA B
Cameron Station, Alexandria	CC	AA
Ft. Eustis, Lee Hall	BB	AA
Ft. Monroe, Hampton	BB	AA AA
Alexandria	BB	AA
Langley Research Ctr., Hampton	BB	AA AA
Ft. Lee, Petersburg	BB	AA AA

Washington		
Vancouver Brks	BC	AA
Ft. Lawton, Seattle	CC	AB
Paine Field, Everett	BB	AA
Ft. Lewis, Tacoma	CC	BB
West Virginia		
No Posts		
Wisconsin		
Milwaukee	CC	AB
Wyoming		
No Posts		
Miscellaneous		
Howard AFB, APO 34006 CZ	AA	AA AA
Ft. Clayton, APO 09827 CZ	AB	AA AA
Ft. Amador, APO 09827 CZ	AA	AA AA
Ft. Buchanan, APO 00934 PR	AB	AA A
Honduras, Tegucigalpa, HO	CC	AA AA

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